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FACULDADE DE CIÊNCIAS
DEPARTAMENTO DE ENGENHARIA GEOGRÁFICA, GEOFÍSICA E ENERGIA

Dynamic Insulation as a strategy for Net-Zero Energy Buildings

João Tiago Lopes Alves Homem

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Dissertação orientada por:
Prof. Doutora Laura Aelenei (FCUL)
Roel Loonen (TU Eindhoven)

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Resumo

Atualmente, o consumo de energia nos edifícios representa cerca de 40% da necessidade total de energia primária na União Europeia (UE), assim como cerca de 36% das emissões de gases com efeito de estufa (GEE). Desta forma, "o setor dos edifícios" tem um potencial significativo em matéria de poupança de energia, e para o que isso pode representar em termos de redução de GEE, não só na construção de novos edifícios, mas também na renovação dos existentes. A sua importância é, por isso, fulcral para se atingir as metas 20-20-20 do *Roadmap* 2050 da UE. Como tal, a regulamentação lançada pela UE ao nível do desempenho energético dos edifícios tem vindo a incorporar um novo conceito: o de edifícios de balanço energético nulo ou quase nulo (nZEB ou NZEB). Este conceito baseia-se na cobertura do consumo de energia do edifício através de fontes de energia renovável, de produção local ou nas proximidades (*nearby*). No entanto, o primeiro passo para se atingir o objetivo pretendido consiste na implementação de medidas de eficiência energética que permitam reduzir as necessidades energéticas do edifício para um valor mínimo economicamente viável a ser colmatado por recurso a fontes de energia renovável.

Ao nível da envolvente dos edifícios, o foco da legislação da UE consiste em atingir níveis de maior isolamento térmico e maior estanquicidade para reduzir o consumo de energético. Embora o aumento do nível de isolamento térmico contribua para diminuir as perdas de calor através das fachadas dos edifícios no Inverno, no Verão poderá ser desadequado pois restringirá o fluxo de calor quando se pretende extrair os ganhos de calor indesejados. Deste modo, os edifícios com isolamento térmico elevado têm um maior risco de sofrerem problemas de sobreaquecimento, uma vez que a temperatura interna responde mais rapidamente ao aumento dos ganhos solares e internos. Uma solução para esse problema poderá passar pela utilização de elementos de fachada com um coeficiente de transmissão térmica (U) variável, o que, por exemplo, permitiria "desligar/desconectar" o isolamento térmico durante a noite no Verão.

A existência de um U variável, permitiria fazer uma gestão das trocas térmicas entre os ambientes interior e exterior de acordo com as temperaturas registadas. Para atingir esse fim, a aplicação de elementos ou sistemas de isolamento dinâmico/adaptativo aparece como uma possibilidade interessante. Estas soluções são alternativas ao convencional procedimento de aumentar a espessura de isolamento térmico para evitar as perdas térmicas, uma vez que apresentam um comportamento dinâmico permitindo uma maior flexibilidade térmica e energética dos edifícios. Em comparação com o isolamento "estático", os elementos de isolamento dinâmico podem exibir parâmetros térmicos variáveis, como condutividade térmica e emissividade. Estes permitem que as fachadas dos edifícios sejam elementos responsivos em relação ao ambiente térmico exterior.

Neste projeto, o objetivo principal foi o estudo do potencial da aplicação de elementos ou sistemas de isolamento dinâmico ao nível dos edifícios. Para tal, o projeto foi estruturado em várias etapas.

O primeiro passo passou por fazer uma revisão bibliográfica dos elementos e sistemas que apresentassem um comportamento térmico dinâmico e que pudessem ser utilizados ao nível dos edifícios desempenhando a função de isolamento térmico. Após feita essa identificação, os elementos mais relevantes foram descritos e classificados de acordo com o mecanismo utilizado para obter um comportamento dinâmico (processos de transferência de calor: condução ou convecção) e a sua escala de atuação (macro, micro ou nano).

Seguidamente, o próximo passo foi determinar como efetuar a simulação computacional do desempenho térmico dos elementos de isolamento dinâmico. Ao nível da simulação de parâmetros que variem ao longo

do tempo, verificou-se que os vários tipos de software existentes apresentam bastantes limitações, uma vez que quando foram concebidos a dinamicidade das propriedades dos materiais não era uma questão central. Para fazer esse tipo de análise, concluiu-se que o EnergyPlus era o software mais adequado por apresentar maiores capacidades para a modelação de fachadas adaptativas.

Para prever o desempenho de elementos de isolamento dinâmico, no EnergyPlus, podem ser utilizadas duas abordagens: a *ClassList MovableInsulation* e o grupo *EnergyManagementSystem* (EMS). Na primeira, a resistência térmica do elemento de isolamento é determinada em função de horários (schedules) que reproduzem a alteração da mesma em diferentes condições ao longo do tempo, sendo esta realizada num regime de *post-processing*. A segunda abordagem permite definir o comportamento de um dado elemento de isolamento dinâmico, ao longo da simulação, de acordo com determinados parâmetros físicos definidos como sensores (ex.: temperatura exterior, radiação incidente numa fachada, temperatura interior)

Após serem detalhadas as abordagens existentes no EnergyPlus que podem ser utilizadas para simular estes elementos de isolamento dinâmico, foi feita uma análise comparativa de modo a concluir qual a abordagem que mais se adequa ao objetivo pretendido. Embora o EMS seja mais realista, uma vez que permite fazer um controlo ao longo da simulação, apresenta algumas limitações que fazem com que não seja possível a substituição das construções. Deste modo, a abordagem utilizada para efetuar o caso de estudo foi a *ClassList MovableInsulation*.

Aplicando a abordagem atrás mencionada, foi desenvolvido um caso de estudo representando um modelo ilustrativo de uma moradia localizada em Lisboa, Portugal. A análise realizada focou-se no período de Verão (estação de arrefecimento) durante o qual se estudou o efeito da aplicação de uma layer de isolamento exterior removível (*movable insulation*), de 10 cm de poliestireno expandido (EPS), na redução do sobreaquecimento no interior da moradia (quando a temperatura média do ar é superior a 25°C). Com uma estratégia de controlo adequada, verificou-se uma redução, face ao cenário base, de 51% nas horas de sobreaquecimento e de 35% no consumo de energia elétrica para arrefecimento.

Finalmente, foi feita uma análise comparativa entre a solução anterior e a aplicação de um sistema de ventilação natural com uma taxa de ventilação de 5 renovações por hora. Para esse ultimo cenário, verificou-se uma redução significativamente maior, face ao cenário base, tanto no consumo de arrefecimento (cerca de menos 67%) bem como nas horas de sobreaquecimento (68% menos). A utilização conjunta da *movable insulation* e da ventilação natural permitiu uma redução de 72% no consumo de energia para arrefecimento e de cerca de 80% nas horas com temperaturas interiores superiores a 25°C.

Palavras-chave: Isolamento Dinâmico, Edifícios de Balanço Energético Nulo, EnergyPlus, Movable Insulation, Energy Management System (EMS)

Abstract

The current focus when it comes to size thermal insulation systems is to reach the highest insulation level. Besides the fact that the goal of this approach is to reduce the heat losses, especially during the winter, this can bring severe overheating problems that need to be solved. This way, dynamic insulation elements appear as a possible solution to this problem as they allow to have an adaptive range of their thermophysical properties, such as thermal conductivity, instead of a static value registered on the conventional insulation systems. There are several different materials and systems, with different mechanisms of control and resultant adaptive ranges, that can be used as dynamic insulation elements. Nowadays, in terms of simulation framework, the most suitable software to predict the performance of dynamic insulation elements is EnergyPlus, which offers two approaches to do it: the Movable Insulation Actuator and the Surface Construction State Actuator (on the Energy Management System group). After doing a comparison between these two approaches, it was concluded that the second one is the most promising, but due to limitations regarding implementation details, it was not used for the case-study analysis. By using the MovableInsulation Actuator in the case study analysis, for the climate of Lisbon, Portugal, it was concluded that the application of a removable insulation layer (10 cm of EPS), with an optimized control strategy, achieved 51% decrease on overheating hours and 35% of decrease on the cooling energy demand, in comparison with a base case. Moreover, the use of movable insulation in combination with a system of natural ventilation can allow greater savings in terms of cooling and a more significant reduction on the overheating hours.

Although some of the details of how to assess the dynamic insulation elements become clearer throughout this analysis, there is much more work and research that needs to be done to accelerate the product development and technology implementation of these systems.

Keywords: Dynamic Insulation, Net-Zero Energy Buildings, EnergyPlus, Movable Insulation, Energy Management System (EMS)

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Abbreviations and Symbols

ACH	Air Changes per Hour
BESTEST	Building Energy Simulation Test
BPS	Building Performance Simulation
CTF	Conduction Transfer Function
DOE	U.S. Department of Energy
EBC	Energy in Buildings and Communities Programme
EMS	Energy Management Systems
ERL	EnergyPlus Runtime Language
EPBD	Energy Performance of Buildings Directive
EPS	Expanded Polystyrene
EU	European Union
FESU	Facade Element with Switchable Insulation
GHG	Greenhouse Gases
GIM	Gas Insulation Materials
GMT	Greenwich Mean Time
HVAC	Heating, Ventilation and Air Conditioning
IEA	International Energy Agency
LST	Local Solar Time
NIM	Nano Insulation Materials
nZEB	Nearly-Zero Energy Building
NZEB	Net-Zero Energy Building
PCM	Phase Change Materials
PUR	Polyurethane
RES	Renewable Energy Sources

TARP	Thermal Analysis Research Program
VIM	Vacuum Insulation Materials
VIP	Vacuum Insulation Panels
VSDI	Void Space Dynamic Insulation
XPS	Extruded Polystyrene

Ar	Argon
H_2O	Water
g-value	Solar Heat Gain Coefficient (SHGC)
R_c-value	Thermal Resistance (m^2.K/W)
R_{ins}	Total Thermal Resistance in the insulating state (m^2.K/W)
R_{cond}	Total Thermal Resistance in the conducting state (m^2.K/W)
R_{conv}	Thermal Resistance regarding heat transfer by convection (m^2.K/W)
R_p	Thermal Resistance regarding heat transfer by conduction (m^2.K/W)
R_{rad}	Thermal Resistance regarding heat transfer by radiation (m^2.K/W)
T_{in}	Indoor Mean Air Temperature (°C)
T_{out}	Outdoor Dry-Bulb Temperature (°C)
U-value	Thermal transmittance (W/m^2.K)

Greek Letters

α	Solar altitude (º)
δ	Solar declination (º)
ϕ	Latitude (º)
ω	Hour angle (º)
λ	Thermal conductivity (W/m.K)

Chapter 1 – Introduction

1.1 – Context about Net-Zero Energy Buildings

Nowadays, in Europe, energy consumption in buildings accounts for around 40% of total primary energy demand and 36% of total greenhouse gases (GHG) emissions [1]. This way, the 'buildings sector' has been acknowledged by the European Union (EU) has having a significant potential regarding energy savings (and consequently in GHG emissions) in the construction of new buildings and in the refurbishment of existent ones. This sector is central not only to achieve the EU 20-20-20 targets but also to meet the long term goals defined in the low carbon economy roadmap 2050 [1]. Thereby, the most important action was to launch several regulations to converge the built environment to the concept of Net-Zero Energy Buildings (NZEB). The main legislative document at EU level with the goal to increase the energy efficiency in buildings is the Energy Performance of Buildings Directive – Recast (EPBD Recast, 2010/31/EU), which sets that by 31st of December 2020, all new buildings must be nearly-Zero Energy Buildings (nZEB) [2].

This NZEB concept is based on covering the energy demand through renewable energy sources (RES), produced on-site or nearby [2]. However, first it is mandatory to achieve significant savings at the consumption level, applying energy efficiency measures to reduce energy demand (Figure 1.1). This is the first, and the most important step on the path towards NZEB because it would be financially impossible to cover all the demand just by setting up a massive installed power of renewable energy sources to equal the consumption [3]. Although, there is a great need to improve buildings' performance to meet the requirements of this directive, as a very large percentage of European buildings does not comply with it. Therefore, it is clear that further increasing the energy efficiency in the buildings' envelope elements is of great importance to achieve the Net-Zero Energy concept and develop a whole new generation of buildings in the urban context [4].

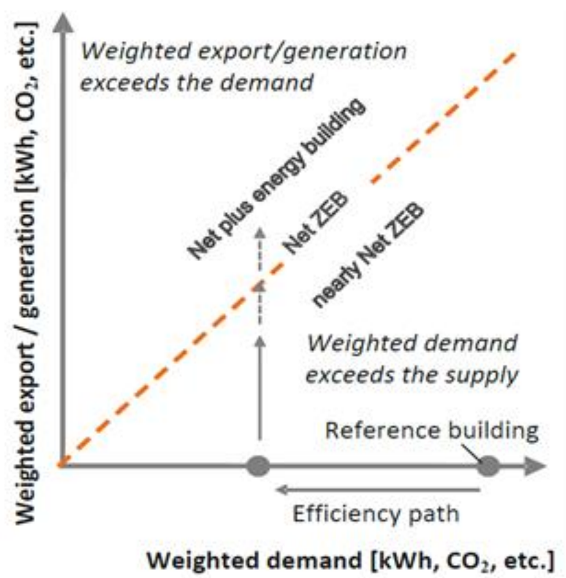


Figure 1.1 – The path toward a Net-Zero Energy Building: first follow the efficiency path and then cover the remaining energy demand by installing renewable energy sources [3]

1.2 – Motivation for the application of Dynamic Insulation

The current focus throughout EU national building regulations is on having higher thermal insulation levels and increased air tightness, in order to reduce energy consumption. [5]. Despite the fact that having a static higher insulation level will contribute to lower the heat losses from buildings in winter, it will also restrain heat flow across the wall when this is potentially beneficial. An example of that is during nighttime hours in summer, when it is useful to extract the undesired heat gains, resultant of internal loads and solar gains through the windows, that were accumulated in the building compartments during the day. Highly insulated dwellings have increased risk of experiencing severe overheating problems, as internal temperature responds more rapidly to the increase of solar and internal gains [6].

To avoid overheating, façade elements with switchable U-value could be a possible solution, which would allow to ‘switch off’ the thermal insulation during nighttime in summer [7], [8]. A low U-value would help to keep the heat loads indoors when heating is needed while a high U-value would allow cooling the building when the outdoor temperature is lower than the indoor temperature [9]. To address this, dynamic/adaptive insulation solutions are interesting alternatives to the regular one-dimensional way of only adding more insulation and improving air tightness. This concept can be applied on either opaque or translucent elements, but the focus of this study will be on the opaque façade.

The application of dynamic insulation elements fits into the concept of the responsive/adaptive building envelopes/facades, because by adjusting their thermo-optical properties, they allow to actively and selectively manage the energy and mass transfer between the building and its surrounding environment (Figure 1.2). This has been seen as a breakthrough approach, not only contributing to improve the energy flexibility of the buildings but also as a way of improving the indoor environment quality for its occupants [10].

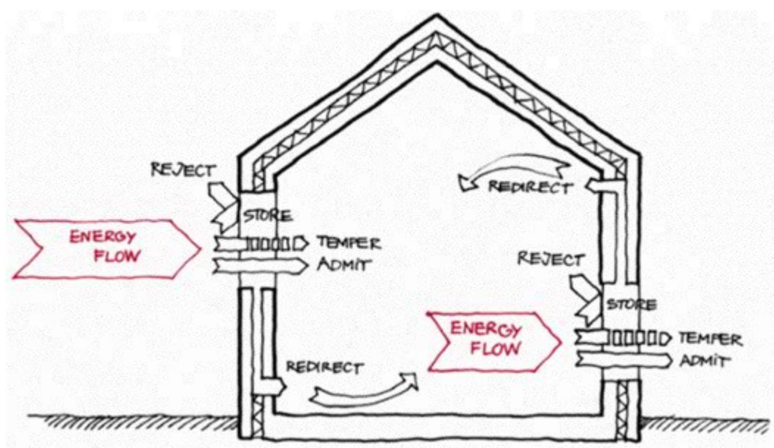


Figure 1.2 – Illustration of dynamic energy flows and interactions in buildings with adaptive facades (from: IEA EBC Annex 44, adapted by Fernández Solla [47])

1.3 – Role of the BPS tools

Nowadays, there is a need to assess the performance, to support and accelerate the implementation of these adaptive elements. To do so, Building Performance Simulation (BPS) tools play a major role in the process, as they allow to assess different design and control strategies that maximize building’s performance and support product development [11]. However, the application of BPS to study the performance of these elements when integrated at a building level has not been sufficiently explored to reach a point where it is possible to have a clear level of understanding about what are the most important aspects in which the simulation strategy should focus on [12]. The fact that information available on this subject is limited and dispersed, and that current simulation tools were not originally developed for this purpose states a big challenge for a successful design of adaptive facades and leaves limited guidance to the BPS users [10]. Loonen et al. (2016) identified that in comparison to conventional static facades, there are two important additional requirements when it is needed to predict the performance of adaptive façade systems: modelling the time varying façade properties and the dynamic operation of façade adaptation.

1.4 – Research goals

The main goals of this dissertation were to:

- Perform an extensive study of different insulation materials/systems which can be integrated at the building level to achieve a dynamic behavior.
- Develop a simulation strategy to predict the performance of dynamic insulation elements.
- Perform an illustrative case study to conclude about the effect of the application of dynamic insulation on the overheating problem during the cooling season.

1.5 – Structure of the thesis

This dissertation is organized as follows:

- In chapter 2, a state-of-art overview is given, whereas several dynamic insulation materials/systems are described and categorized by scale and range of control
- In chapter 3, the simulation approaches available in EnergyPlus to predict the performance of dynamic insulation elements are described and compared, and some preliminary results regarding their use are presented as well.
- In chapter 4, the case study is throughly described. The details about the location, the geometry of the dwelling, the simulation input data, the overheating problem and respective control strategy are referred in detail.
- In chapter 5, the results of the case study analysis are outlined
- Finally, in chapter 6 the main conclusions of the project are outlined and the recommendations for product development and future work are given

Chapter 2 – State-of-the-art overview

2.1 – Background

Over the years, several different thermal insulation materials have been developed with the purpose of thermally isolate the inside and outside environments at the building level. The ultimate goal is to achieve significant energy savings while maintaining high levels of indoor thermal comfort. When it comes to select a certain insulation material, the focus is to achieve the highest possible thermal insulation values by picking the ones that have higher thermal resistances. This means materials with lower thermal conductivity in order to reach as low thermal transmittance (U-value) as possible on the building's façade.

Nowadays, there are numerous static insulation materials that can be applied, from traditional/conventional to state-of-the-art (high-performance) thermal insulation whereas the latter exhibit significantly lower values of thermal conductivity. Current conventional insulation materials such as mineral wool, expanded or extruded polystyrene (EPS, XPS), cellulose, cork and polyurethane (PUR) have relatively high thermal conductivities values, ranging from 20 to 50 mW/(m.K). Although, this range can vary in regard with moisture content, mass density, temperature and possible perforation of the materials [13], [14].

To decrease the U-value of the façade without ever increasing the thickness of the insulation layer, new high-performance insulation materials have been developed, which could achieve the lowest thermal conductivity values up-to-date. Vacuum insulation panels (VIP) and aerogels, are examples of some of the solutions that can be applied currently, which can reach values of conductivity as low as 3 mW/(m.K). There are also some future materials and solutions that are being researched such as vacuum insulation materials (VIM), gas insulation materials (GIM) and nano insulation materials (NIM), with an overall thermal conductivity of less than 4 mW/(m.K).

In Table 2.1, the referred traditional and high performance insulation materials are displaced in descending order of thermal conductivity.

Table 2.1 – Comparison between traditional and state-of-the-art insulation materials [14]

	Material	Thermal Conductivity
Conventional	Cellulose Cork	40-50 mW/(m.K)
	Mineral Wool Expanded Polystyrene (EPS) Extruded Polystyrene (XPS)	30-40 mW/(m.K)
	Polyurethane (PUR)	20-30 mW/(m.K)
State-of-the-art (High-performance)	Aerogels Vacuum Insulation Panels (VIP)	13-14 mW/(m.K) 3-4 mW/(m.K)
	Vacuum Insulation Materials (VIM) Gas Insulation Materials (GIM) Nano Insulation Materials (NIM)	< 4 mW/(m.K)

Apart from the solutions previously referred, there is also a relatively new concept that can offer thermal insulation features: phase-change materials (PCM). As the name implies, these materials change from solid state to liquid state when heated, absorbing energy (endothermic process), and from liquid to solid when the temperature drops releasing energy (exothermic process) [14]. Although they are not seen as thermal insulation materials, they can be used for interesting thermal building applications, either being used as separated components in building constructions or impregnated directly into building materials. They make use of the thermal mass to reduce fluctuations in air temperature shifting the cooling loads towards off-peak periods, offering the possibility to store both sensible and latent heat [15].

However, as introduced in chapter 1, the ideal scenario is to have thermal insulation solutions that not only are able to achieve the lowest thermal conductivity values as possible, but also provide the possibility to control it within a desirable range: thus, it would be possible to control the heat flow through the façade depending on the indoor-outdoor temperature difference [12].

2.2 – Dynamic Insulation Solutions

In comparison with the static insulation, dynamic insulation elements can exhibit changeable thermal parameters, such as thermal conductivity and emissivity. These allow buildings' facades to be responsive elements regarding the surrounding thermal environment. In addition, Loonen et al. (2014) showed that dynamic insulation elements can also be used to achieve variable thermal storage by coupling or decoupling a storage wall from a compartment, as the dynamic insulation layer is able to change between states of low and high conductivity [16].

In this subchapter, several insulation elements are described and classified according to the mechanism used to achieve a dynamic behavior and scale of actuation. In the first place, when the main heat transfer process is convection through air or liquid, the level of actuation is at a macro-scale [12]. On the other hand, when the control is based on controlling the heat conduction by varying the pressure of a gas, changing the path of the gas molecules or its interaction with the surface of the insulation panel, the level of actuation is at a micro/nano-scale [12]. Finally, a movable insulation system is described.

2.2.1 - Macro-scale actuation

The concept of dynamic insulation is not new, with research dating back to the 1970s and several definitions available from literature. It can be used either in place or in tandem with conventional insulation [17]. Most of the macro-scale applications for dynamic insulation are achieved by incorporating in the façade a system based on heat convection either through air or liquid, to control the heat transfer [12].

2.2.1.1 – Systems based on heat convection through air to control the heat transfer

1 - One of the generic definitions of them is given by Arquis and Langlais, who set that there are three types of generic dynamic insulation systems that can be applied in buildings: parietodynamic, permeodynamic, and thermodynamic insulation [18].

Parietodynamic insulation elements have a channel where the air flow is confined, surrounded by materials impermeable to the airflow. The cold air supplied from outside preheats, by circulating on a cavity within the wall, before entering inside the building, reusing the exhaust air from indoors as an heat exchanger [19]. This process is sketched in Figure 2.1. This is somewhat similar to a ventilated façade. An example of this insulation solution is called Void Space Dynamic Insulation (VSDI) which can achieve a range of U-values between an average of 0.092 W/m^2.K in open mode and 0.20 W/m^2.K in static 'no airflow' mode [17].

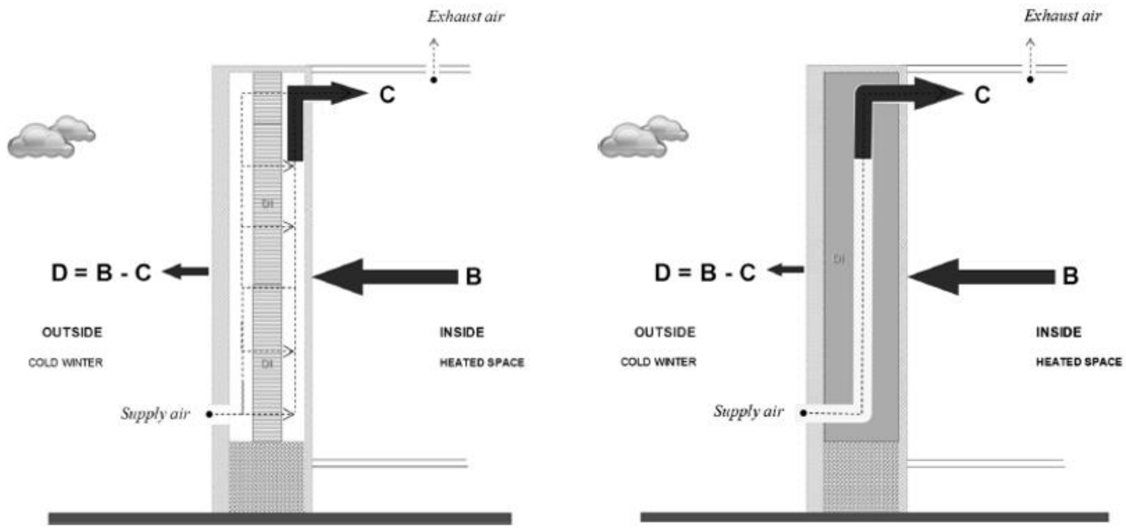


Figure 2.1 – Permeodynamic (left) and parietodynamic (right) insulation sketches [17]

In the case of the permeodynamic insulation (or breathing wall), there is an air porous panel that works as a cross-flow heat-exchanger, with a controllable airflow between inside and outside environments [20], [21]. The U-value is a function of the air-flow, as presented in the graph of Figure 2.2.

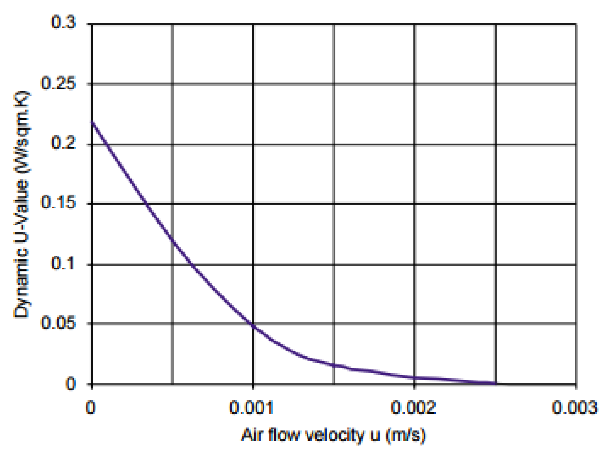


Figure 2.2 – Dynamicity of the U-value according the air flow velocity through a breathing wall [21]

Finally, on the thermodynamic insulation, despite being similar to the permeodynamic, the air circulates in a closed circuit and a separate heat exchanger is necessary.

2 - Pflug et al (2014), proposed and studied a translucent dynamic insulation system denominated FESU (façade element with switchable insulation), which consists on a closed model with one or various insulation panels, where the convection is controlled [7]. This element can be in two states, insulating or conduction state (Figure 2.3).

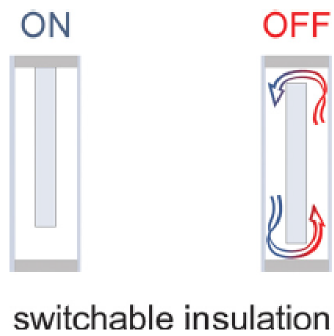


Figure 2.3 – FESU in the insulating state (left) and also on conducting state (right) [7]

When it is in insulating state, the translucent panel is at the top avoiding the convection around the panel, existing this way three insulating layers (two of air and one insulation panel). On the other hand, when the system is in conducting state, the panel is a vertical middle position and there is convection around the panel due to a driving pressure difference between the back and front, allowing the heat transfer through the wall. There is a U-value range between 0.7-1.9 $W/m^2.K$, depending on the difference of temperatures between indoors and outdoors (Figure 2.4).

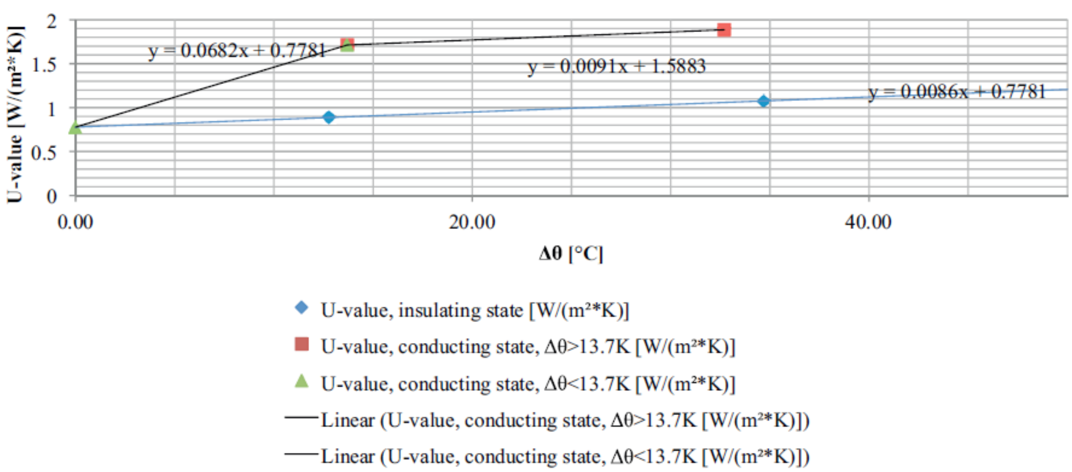


Figure 2.4 – Variation of the U-value in both insulating and conducting state depending on the indoor-outdoor temperature difference [7]

2.2.1.2 – Systems based on heat convection through a working liquid to control the heat transfer

There are several systems that use water or other working liquids to control the heat transfer through the buildings' façade. This is not a new concept, with related systems dated back to the 1980s.

1 - Dijk et al. developed a 'High Performance Passive Solar Heating System' which allowed not only to transfer the collected solar heat through heat pipes but also to store it in a latent heat storage section. These heat pipes, incorporated on the insulation layer act as thermal diodes, transferring the heat from the collector to the back of the insulation layer but not doing it in the reverse direction. Regarding the latent heat storage, it can be achieved either with a storage section of phase-change materials or water [22]. A scheme presenting the composition and the way of functioning of this system is given by Figure 2.5.

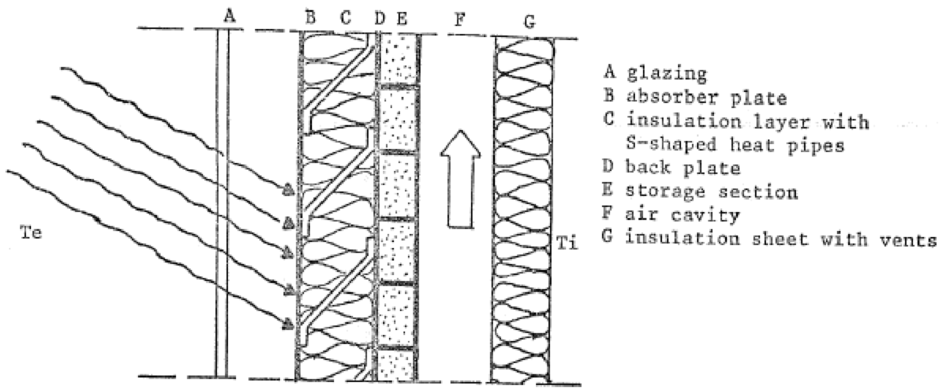


Figure 2.5 – Outline of the system [48]

2 - Numerous researchers have studied and proposed the application of bi-directional thermodiodes [23]–[26]. In parallel with the concept of electric diodes, these systems establish a favorable direction of the heat flow, providing insulation on the other direction, with a principle of functioning based on the thermosyphon effect. This allows, for instance, to direct the heat flow to the wall during a warm day and work in the reversed direction when the stored energy in the system is need indoors, as shown in Figure 2.6.

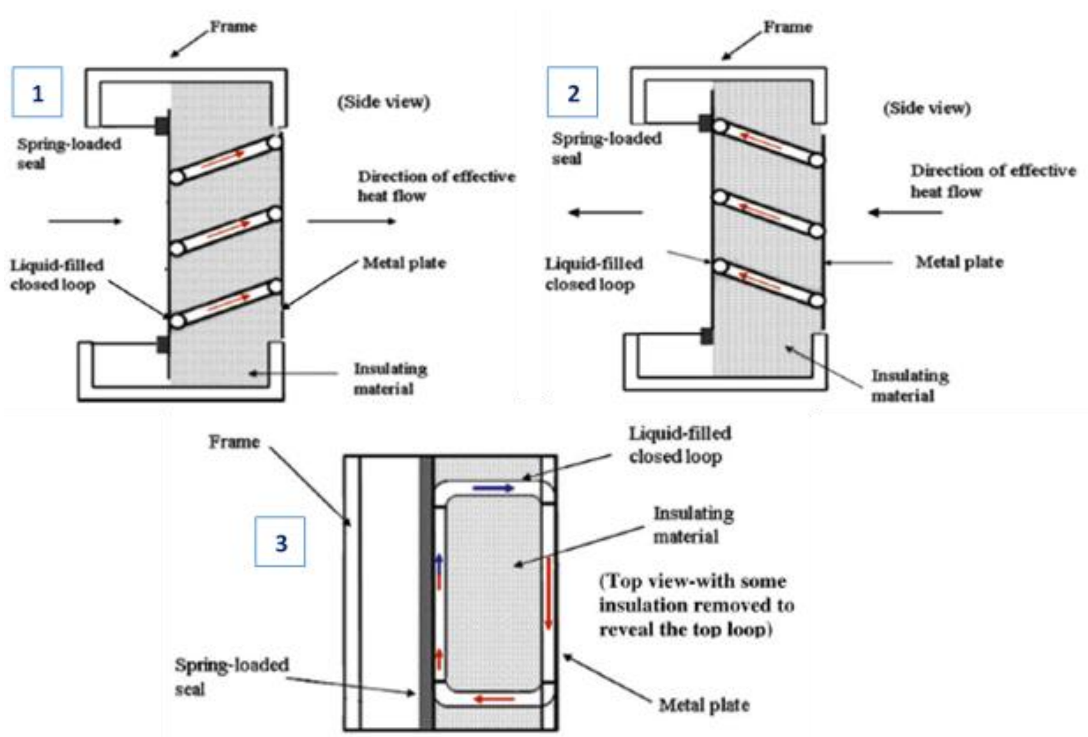


Figure 2.6 – Conceptual design of a bi-directional thermodiode. Forward (1) or backwards (2) heat flow direction modes can be reversibly changed via rotable joints. A top view of the system (3) is also shown [24]

Varga et al. (2002) also tested bi-directional thermodiode panels incorporating heat pipes and obtained a range of apparent conductivities between 0.07 W/m.K in backward mode and a maximum of 0.35 W/m.K in forward mode (being this last one between three to five times higher than in backward mode depending on the temperature difference) [26].

3 – Al-Nimr et al. (2009) designed a different solution to what they denominated by a ‘smart thermal insulation system’. The principle of functioning of this system is based on the idea of filling a gap inside a slab wall with rather a very low conductivity fluid (e.g. argon with k = 0.0179 W/m.K) when it’s needed to provide a good insulation or a very high conductivity fluid (e.g. water with k = 0.64 W/m.K) when the system is required to be a conductor. As shown in Figure 2.7, there are two storage tanks separated by a movable partition which moves to the left or to the right depending on the driving forces. When there is a need to have a system in insulating mode, the partition moves to the left to fill the gap with the low k fluid from the storage tank on the right. When the system needs to be in conduction state, it works the other way around, with the movable partition moving to the right [27].

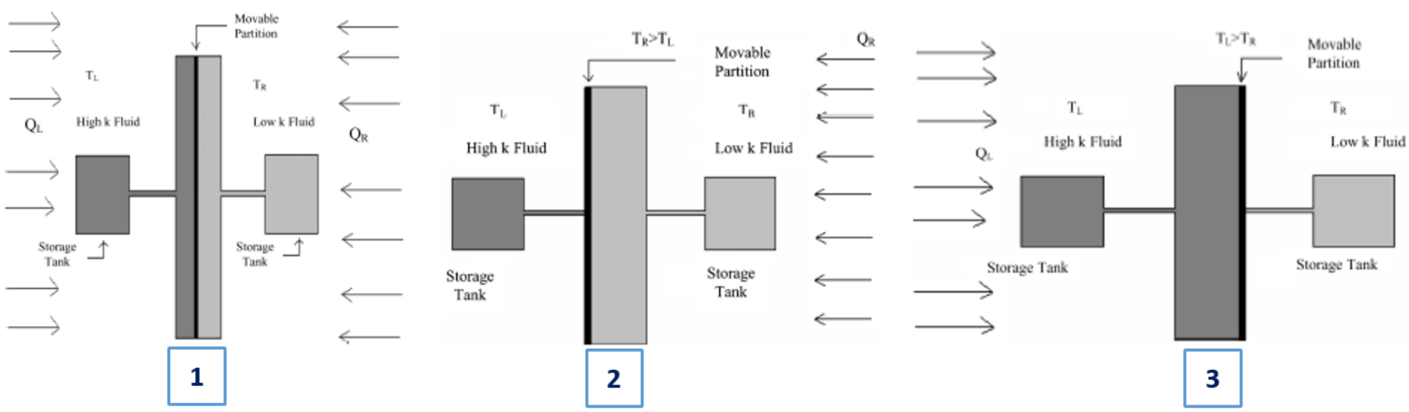


Figure 2.7 – Basic sketch of the smart thermal insulation system (1), in the insulating mode (2) and in the conduction mode (3). Change between modes is achieved via a movable partition on the slab wall [27]

2.2.1.3 – Active Insulation System

The Dutch company P&H Advisors proposed the concept of Active Insulation, which has the possibility to turn the insulation between an ‘on’ and ‘off’ functions [28], [29]. The principle of functioning and composition of this system are represented in Figure 2.8.

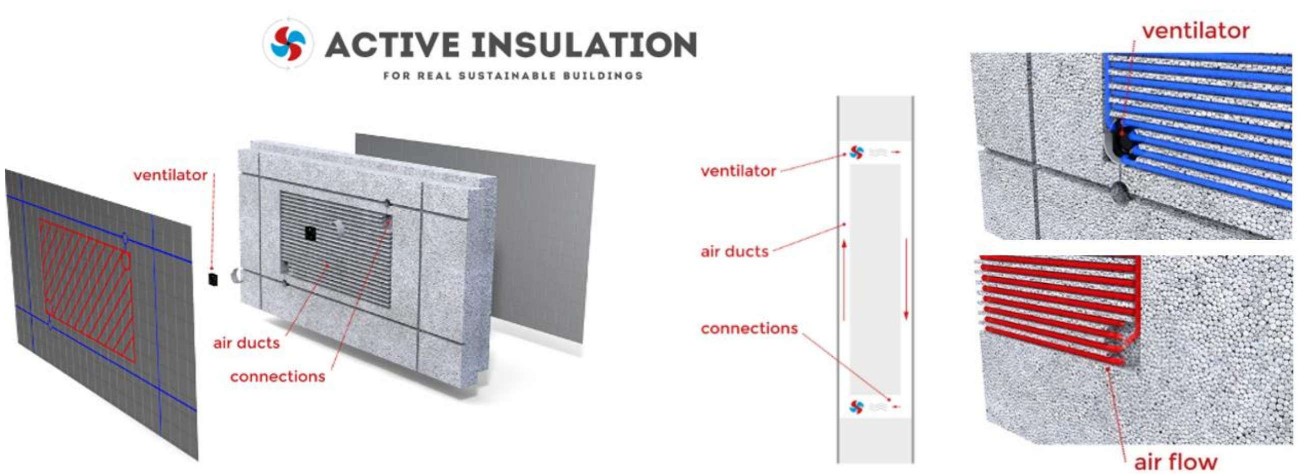


Figure 2.8 – Principle of functioning of Active Insulation [28]

In this Active Insulation system, a structure of air ducts is placed from the top to the bottom on both sides of a conventional hard insulation board. Inside them, two low voltage ventilators are placed, on the top and bottom of the board, to induce forced ventilation which will allow for heat or cold air to flow from outside to inside, or the other way around [28], [29]. This way, a short circuit is created between the two zones around the system bypassing the actual insulation board.

When the sun hits the outside wall, the air inside the ducts gets warmer. If heating is desirable, this air can be pumped by the ventilators towards the inner side of the insulation. For cooling is the other way around. Whenever the ventilator is switched on, the insulation board is turned off and vice-versa. If the ventilators were driven by a temperature sensor, the insulation could become an active element of heating and cooling buildings' systems.

2.2.2 – Micro/Nano-scale actuation

Different approaches have been given either at a micro or nano scale to achieve dynamic insulation level. These solutions control thermal conduction by selecting different strategies: by varying gas pressure, the mean free path of gas molecules or gas-surface interaction in an insulation panel [12].

2.2.2.1 – Systems based on varying the pressure of a certain gas to control conduction

1 - This is not a new concept, having been researched by Xenophou (1976) who submitted a patent about a system which controlled the thermal transfer by regulating the pressure of a partial vacuum between spaced steel panels which form a wall structure. By increasing the pressure of the vacuum, it was possible to decrease the heat flux through the walls, maintaining the ambient temperature in the structure (and the other way around) [30].

2 - Benson (1994) studied a variable-conductance vacuum insulation (VCI) material. In this insulation material, there is a small metal hydride connected to the vacuum envelope which reversibly absorbs/desorbs hydrogen. As illustrated in the graph of Figure 2.9, this hydrogen can change its pressure within a range from less than 10^{-6} to as much as 1 torr (1 torr $\simeq$ 133.3 Pa), which allow to achieve a variable thermal transmittance [31].

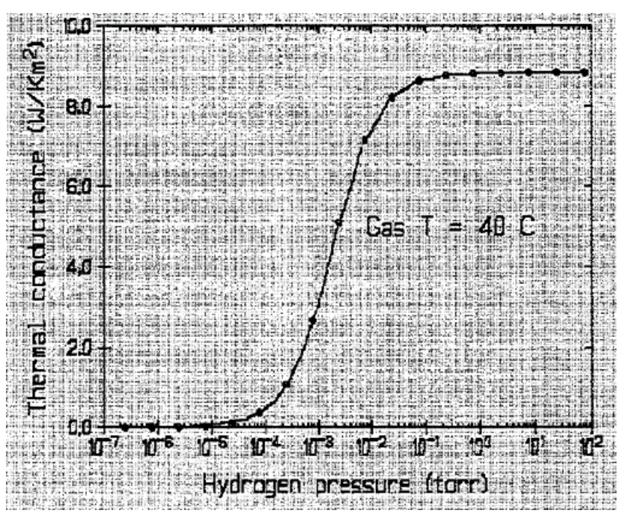


Figure 2.9 – Variation of the thermal conductance through the 20 mm thickness of a VCI panel as a function of the internal hydrogen pressure [31]

3 – Horn et al. (2000) designed a switchable insulation system similar to the one developed by Benson. By using a metal hydride to change the pressure of hydrogen gas inside a panel, it is possible to reversibly change the thermal conductivity between 0.14 W/m.K in the conducting state and 0.003 W/m.K on the insulating state [32], [33], as illustrated in Figure 2.10.

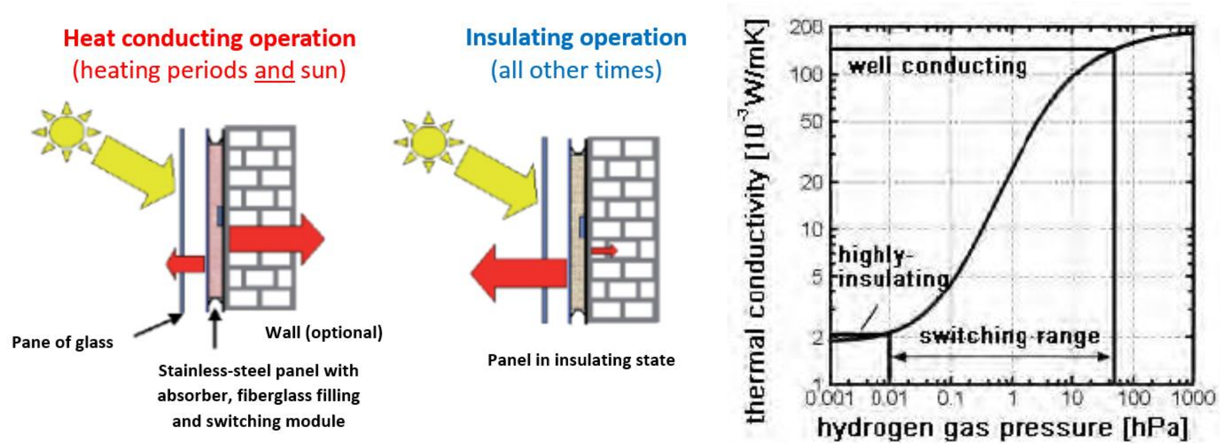


Figure 2.10 – Principle of functioning (on the left) (adapted from Burdajewicz, Korjenic, & Bednar, 2011) and range of variation of the thermal conductivity (on the right) [49]

4 - Berge et al. (2015), developed an insulation system with two different nano-porous materials where its internal pressure is varied to achieve a variable U-value. These materials were aerogel blanket and fumed silica (structure of a Vacuum Insulation Panels, VIP) and measurements of thermal conductivity were made when the air pressure was varied between 1 kPa and the atmospheric pressure (100 kPa) using a vacuum pump [9]. A variation of the thermal conductivity of around 3 times more for the fumed silica (7-19 mW/m.K) and less than 2 times for the aerogel blanket (11-17 mW/m.K) was measured (Figure 2.11).

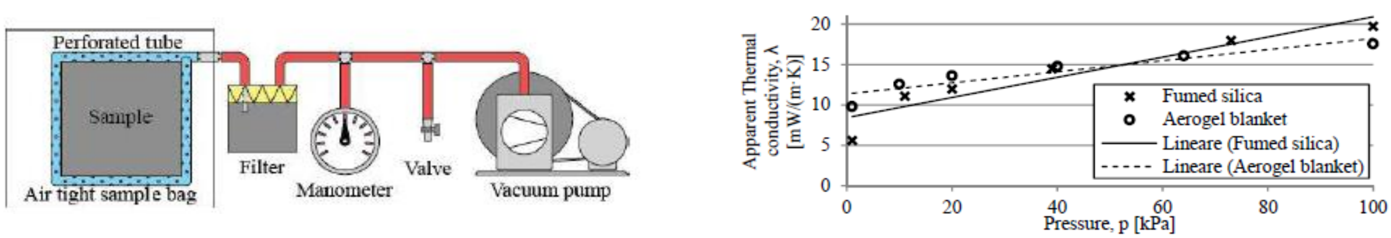


Figure 2.11 – Schematic of the equipment for the measurements (on the left). Variation of the apparent thermal conductivity with the increase of air pressure for both materials (on the right) [9]

2.2.2.2 – Systems based on varying the gas-surface interaction in an insulation panel

Kimber et al. (2014), performed a conceptual analysis about a 'smart' multifunctional insulation, where it is possible to switch between insulating (R_{ins}) and conducting states (R_{cond}), by varying the number of layers of air (N) on a multi-layered polymer membrane, as depicted in Figure 2.12. Through each layer of air, there is heat transfer by convection and radiation (R_{conv} and R_{rad} in parallel) and through the interface between layers there is heat transfer by conduction (R_p). By collapsing the wall and removing the air, it is possible to change between insulated and conductive states, whereas radiation and convection resistances are no longer present. This way, it is possible to achieve a changeable thermal transmittance (U-value) [34].

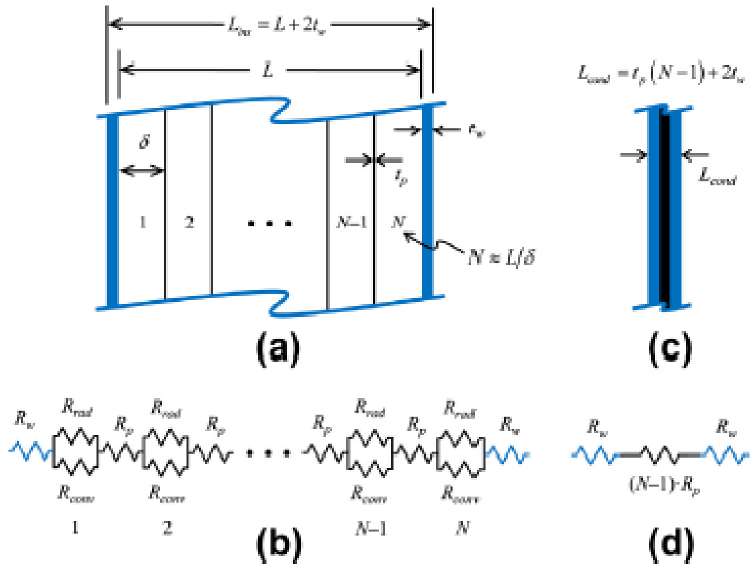


Figure 2.12 – Illustration of adaptive multilayer wall: (a) is the insulated state, with N layers of air and its equivalent thermal resistance network is presented below (b); (c) is the configuration for collapsed wall or conductive state whereas (d) is its equivalent thermal resistance [34]

2.2.2.3 - Systems based on varying the mean free path of gas molecules in an insulation panel

Some recent studies have proved that by changing the direction of carbon nanotubes suspensions in a fluid it is possible to reversibly change the thermal conductivity. Wu et al (2014), studied the effect of varying the temperature on the change of direction of the carbon nanotubes. A change in thermal conductivity from 0.4 to 1.2 W/m.K was registered. [35]. Corinne Baresich et al. studied the effect of applying an external magnetic field to align the carbon nanotubes and consequently achieve a changeable thermal conductivity of the fluids where they are in a suspension [36]. This effect is illustrated in Figure 2.13.

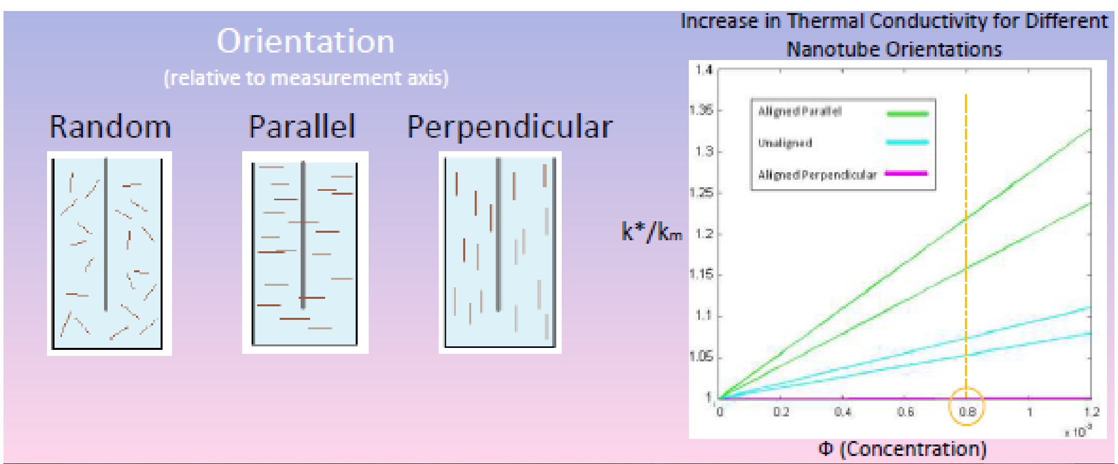


Figure 2.13 – Study of the variation of the thermal conductivity in regard with different nanotube orientations [36]

2.2.3 – Movable Insulation System: Thermocollect

Thermocollect is a movable insulation system that was developed and tested in Austria by Rudolf Schwarznayr. This is an active-façade system which is constituted by a set of automated movable panels placed in front of a massive wall. The system is automated according to the surrounding indoor and outdoor conditions and can reduce both the heat losses during the winter and the heat gains during the summer.

During the winter, the system is typically closed at night in order to minimize the heat losses. However, during the day, in the presence of solar radiation, the panels are automatically opened to allow the solar heat to be stored in the wall. This heat will take a certain delay time to pass through the wall, but then will allow desirable heat gains inside the dwelling during nighttime (when the panels are closed). During the summer, the system is closed during the day acting as an insulation layer. During the night it can be opened to allow the release of unwanted heat gains accumulated during daytime [37]. An illustration of the principle of functioning of this system throughout a winter day is shown in Figure 2.14.

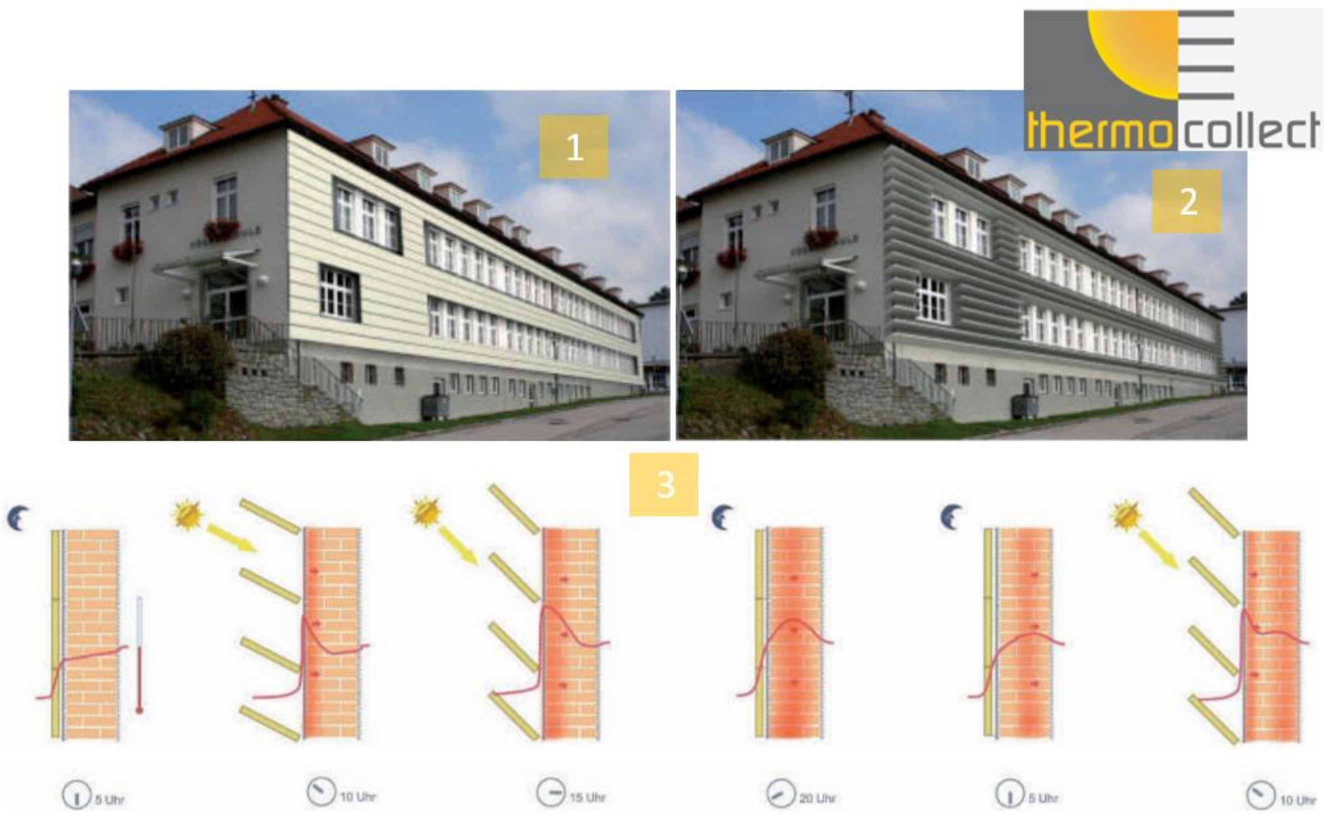


Figure 2.14 – Illustration of the way of functioning of the Thermocollect system [37] . In this system, the exterior movable panels can be either closed (1) or open (2). The goal is to modulate the thermal mass of the wall, as desirable throughout the day (3).

2.2.4 - Comparison

To conclude the state-of-the-art overview, a comparison between the dynamic insulation technologies is presented, in order to compare the range of adaptive control. This analysis is presented in Table 2.2.

Table 2.2 – Comparison of some of the dynamic insulation technologies based on the range of adaptive control available in the literature

Scale	Mechanism of Control	Element Description	Range of adaptive control			Reference
			λ [W/m.K]	**U-value** [W/m^2.K]	**Rc-value** [m^2.K/W]	
Macro	Heat convection through air	Parietodynamic wall – Void Space Dynamic Insulation (VSDI)	-------	0.092-0.20	-------	[17]
		Permeodynamic wall (Breathing Wall)	-------	0-0.21	-------	[21]
		Translucent Dynamic Insulation System: Façade element with switchable insulation (FESU)	-------	0.7-1.9	-------	[7]
		Active Insulation™	-------	-------	-------	[28]
	Heat convection through liquid	Bi-directional thermodiode	0.07-0.35	-------	-------	[26]
		'Smart thermal insulation system': low and high conductivity fluid tanks	0.0179 (Ar) - 0.64 (H_2O)	-------	-------	[27]
Micro/ Nano	Varying the pressure of a gas to control heat conduction	Variable conductance vacuum insulation (VCI) - Adsorption/deabsorption of hydrogen	-------	0-9.0	-------	[31]
			0.003-0.14	-------	-------	[33]
		Variable pressure on aerogel blanket	0.011-0.017	-------	-------	[9]
		Variable pressure on fumed silica (VIP)	0.007-0.019	-------	-------	
	Varying the gas-surface interaction	'Smart' multifunctional insulation – Variation on the number of layers of air	-------	-------	0.118 – 3.70	[34]
	Varying the mean free path of gas molecules	Change in the temperature to vary the direction of the carbon nanotubes suspension in liquid	0.4-1.2	-------	-------	[35]
		External magnetic field applied to change the direction of the carbon nanotubes	-------	-------	-------	[36]

By analyzing the Table 2.2, it is possible to identify a classification challenge: in some elements the values available in literature for the adaptive range are in terms of λ whereas in others they are given in terms of U-value. It is really difficult to classify all these elements together because some refer to materials, which can be classified in terms of λ, or to a whole wall construction, which is classified in terms of U-value. Moreover, when it comes to dynamic systems, it all depends on how they are operated, the control strategy and the dynamic conditions. To conclude, the available information about each element is, most of the times, limited, which difficult even more this comparison.

Chapter 3 – Simulation approaches for performance prediction of dynamic insulation elements

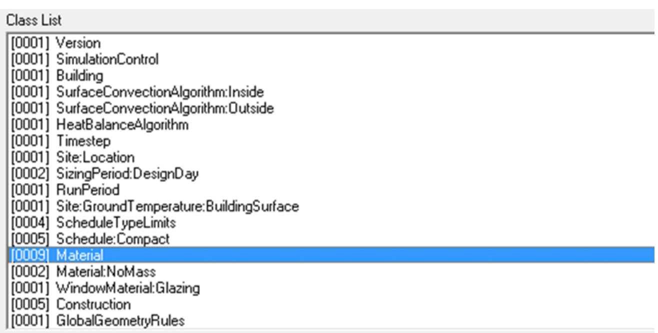
3.1 - Background

Throughout the few publications available regarding dynamic insulation modelling, the information accessible to help the BPS users to learn how to model these elements is somehow vague. This is caused by the fact that nowadays most of these BPS tools present some limitations regarding the simulation of time-variant parameters [16]. Despite the fact that there is a vast number of different software tools available to assess buildings' performance, most of them were designed when the dynamicity of building materials/systems was not a central concern. Therefore, once the simulation is running, building shape and thermophysical material properties are not commonly changeable during this period, which difficult the modelling of those dynamic elements [10]. This way, it is important to develop a simulation assessment strategy to instruct the user on how to model elements which exhibit dynamic thermophysical parameters.

From the software tools available, EnergyPlus is the one which had the most significant improvements in adaptive façade modelling capabilities [10]. This whole-building energy simulation software, developed by the US Department of Energy (DOE), had notorious developments since the introduction of a simplified programming language denominated as EnergyPlus Runtime Language (ERL), which allows to describe and specify the control algorithms. ERL grants the possibility to replicate a building energy management system (EMS) by means of a simulation tool [10].

3.2 – Tools available in EnergyPlus

When the BPS user wants to simulate a specific building, either in terms of energy demand or thermal comfort assessment, he must set the material properties of the elements of the several types of constructions on the building, as shown in Figure 3.1. However, by default, once the simulation is running, the user cannot influence or change the input parameters/properties during the process.



Field	Units	Obj1	Obj2	Obj3
Name		A1 - 1 IN STUCCO	C4 - 4 IN COMMON BRICK	E1 - 3 / 4 IN PLASTER
Roughness		Smooth	Rough	Smooth
Thickness	m	0.025389841	0.1014984	0.01905
Conductivity	W/m-K	0.6918309	0.7264224	0.7264224
Density	kg/m3	1858.142	1922.216	1601.846
Specific Heat	J/kg-K	836.8	836.8	836.8
Thermal Absorptance		0.9	0.9	0.9
Solar Absorptance		0.92	0.76	0.92
Visible Absorptance		0.92	0.76	0.92

Figure 3.1 – Display of some of the class lists, in IDF Editor, that the user can edit before running his simulation in EnergyPlus.

In order to model dynamic insulation elements recurring to EnergyPlus software capabilities, there are two approaches that can be followed, depending on the type of insulation material/system which is going to be assessed through the simulation period. These two approaches are presented in the scheme of Figure 3.2.

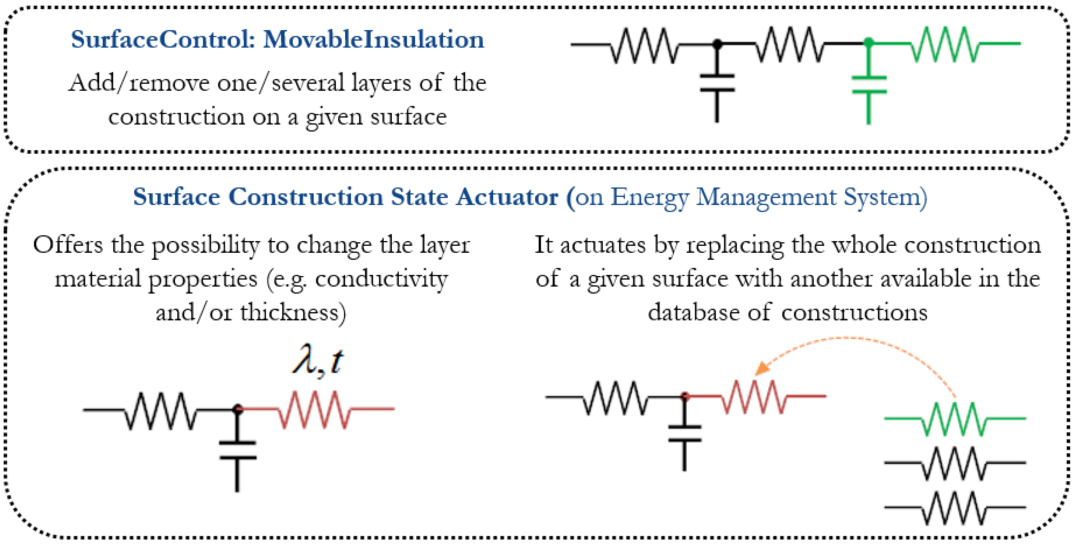


Figure 3.2 – Sketch of the different approaches used in EnergyPlus to model dynamic insulation elements, seen in terms of thermal resistances. The green resistances symbolize the ones being added and the red the ones being removed or having their properties changed.

Firstly, EnergyPlus can simulate movable/removable insulation systems, with the Class List *SurfaceControl: MovableInsulation*. Moreover, EnergyPlus also allows to change the thermophysical material properties by using Advanced Control Methods which emulates the behavior of a real building energy management system (EMS). This is possible using a set of sensors, control logics/algorithms and actuators, defined on several Class Lists available on Group Energy Management System (EMS) in EnergyPlus. On the following subchapters, these two approaches will be briefly described whereas some of implementation details will be referred. Moreover, some preliminary results about their application in EnergyPlus will be also outlined. To finish with, a critical comparison will be done to inform about some of the limitations of each approach.

3.2.1 – *SurfaceControl: MovableInsulation* Class List

3.2.1.1 – Brief description

The application of movable insulation in a building, has the purpose of either trap heat loads inside or to block heat from coming into the dwelling, at a certain desirable period of time. Using the Class List *SurfaceControl: MovableInsulation*, included in *Group Advanced Surface Concepts* in EnergyPlus, it is possible to schedule when to apply an extra layer of insulation on any construction, either on inside/interior, outside/exterior or even on both of its surfaces [38]. This can be scheduled for various times of a day, month or year, depending on how the user defines the schedule that control the behavior of these movable insulation elements. Moreover, *MovableInsulation* can only be applied on regular surfaces (wall, floor, roof, etc.), but not on windows, and it has the possibility for the external movable insulation to be transparent (TIM – transparent insulation material).

3.2.1.2 – Implementation details

As presented in Figure 3.3, there are four fields on this Class List:

- On 'Insulation Type', the user chooses if the movable insulation will be applied on either 'Outside' or 'Inside' of the surface, specified on the next 'Surface Name' field (from *BuildingSurface:Detailed* Class List). If it has to be applied on both surfaces, the user has to create two objects: one for the 'Outside' layer and another for 'Inside' layer.
- On 'Material Name' field, the user defines which is the material of the movable insulation layer (from *Material* or *MaterialNoMass* Class Lists)
- On 'Schedule Name', a schedule is introduced by the user on the IDF Editor or it can be imported from a .txt or .csv file. This schedule should have a real number between 0.0-1.0, at each timestep of the simulation, which works as a fractional multiplier on the thermal resistance (Rc-value) of the material layer defined on the previous field. This way, when it is 1.0 the layer is added and when it is 0.0 the layer is removed.

Field	Obj1	Obj2	Obj3	Obj4
Insulation Type	Outside	Outside	Outside	Outside
Surface Name	SouthWall	NorthWall	WestWall	EastWall
Material Name	SinglePaneOpaque	SinglePaneOpaque	SinglePaneOpaque	SinglePaneOpaque
Schedule Name	SummerControlPeriod	SummerControlPeriod	SummerControlPeriod	SummerControlPeriod

Figure 3.3 – Example of an application of the Class List SurfaceControl: MovableInsulation on IDF Editor. In this case, exterior movable insulation, in all surfaces of the building (S, N, W, E) is controlled according to a specific Summer Control schedule.

As referred before, the schedule introduced can take real numbers between 0.0 and 1.0, which can also allow to model systems with changeable conductivity (λ), and consequently changeable Rc-value, throughout the simulation period.

Knowing that the definition of Rc-value is the thickness (L) of the material divided by its conductivity, $\left(Rc = \frac{L}{\lambda}\right)$, to model an element, with L constant, where it is possible to control its conductivity between λ_1 (initial value of the material, introduced before the simulation) and λ_2, the user have to introduce the fractional multiplier resultant of the ratio $\frac{Rc,2}{Rc,1} = \frac{\lambda_1}{\lambda_2}$, at the desirable timesteps, on the schedule inputted.

3.2.2 – Surface Construction State Actuator on EMS

3.2.2.1 – Brief description

The second option to model dynamic insulation elements is through a high-level control method available in EnergyPlus: Energy Management System (EMS) [38]. EMS uses EnergyPlus Runtime programming language to emulate the controls available in digital energy management systems used in real buildings. These real world systems, composed by sensors, control units/logics and actuators, can be used to control several buildings' systems, which include heating, cooling, ventilation, lighting, on-site power generation, mechanized systems for shading devices, window actuators and façade elements [39].

The class lists available in the EMS group on EnergyPlus are shown in Figure 3.4.

```
Class List

Energy Management System (EMS)
------------------------------
[------]  EnergyManagementSystem:Sensor
[------]  EnergyManagementSystem:Actuator
[------]  EnergyManagementSystem:ProgramCallingManager
[------]  EnergyManagementSystem:Program
[------]  EnergyManagementSystem:Subroutine
[------]  EnergyManagementSystem:GlobalVariable
[------]  EnergyManagementSystem:OutputVariable
[------]  EnergyManagementSystem:MeteredOutputVariable
[------]  EnergyManagementSystem:TrendVariable
[------]  EnergyManagementSystem:InternalVariable
[------]  EnergyManagementSystem:CurveOrTableIndexVariable
[------]  EnergyManagementSystem:ConstructionIndexVariable
```

Figure 3.4 – Class Lists available on the Group Energy Management System (EMS)

Making use of sensors, control algorithms and actuators, EMS overrides specific aspects of EnergyPlus behavior [38]. Firstly, sensors reuse EnergyPlus output variables by measuring a certain parameter regarding the thermal environment. Afterwards, a control algorithm is defined by the user in order to control a certain actuator, based on the information which was provided by the sensors. By means of IF-ELSEIF-ELSE-ENDIF blocks, it will set the behavior of the actuator by proposing a certain action [40]. This process is illustrated in Figure 3.5.

There are several groups of actuators available in EMS, which can be introduced in the class list *EnergyManagementSystem:Actuator*. The ones which allow to control thermo-optical properties of the materials are regarding the Thermal Envelope [40]. The actuators available on this group, allow to control and model several building envelope adaptive elements. One of them is the Surface Construction State actuator which is able to model elements with variable thermo-optical material construction properties [40]. This allow to make insulation changeable in the simulation environment. When modelling a certain element with changeable material properties, the Surface Construction State acts by changing all the existing construction for another which includes a different state of the element, instead of only acting at a material scale. This way, different construction with different thermophysical properties must be created to be used in a sequence defined by the control algorithm.

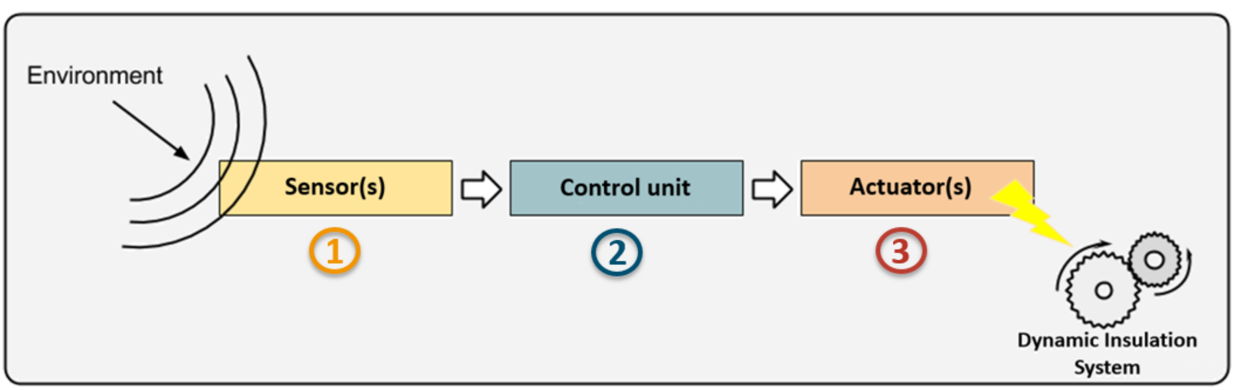


Figure 3.5 – Schematic that presents the main components of an Energy Management System (EMS) and displays the way of functioning in order to control a dynamic insulation system

3.2.2.2 – Implementation details

To the best of our knowledge, there is no simulation strategy available in literature to inform the user of how to model dynamic insulation elements in a simulation environment. This way, a step-by-step procedure of how to use the Surface Construction State Actuator in EMS was given in this subchapter.

Considering a certain insulation element, to be installed on the outside of the exterior walls of a building, that can change its conductivity from λ_1 to λ_2 when the temperature indoors (T_{in}) is higher than the temperature outdoors (T_{out}).

1st step: Define two different materials on *Class List Material*: one with conductivity λ_1 and another with λ_2.

2nd step: Define the construction layers' sequence of the exterior walls on *Class List Construction*, for both two cases

3rd step: Define which construction is chosen to start the first simulation timestep as the standard for all the wall surfaces (on *BuildingSurface:Detailed* Class List):

4th step: Define in Class List *EnergyManagementSystem:Sensor* T_{in} and T_{out} as sensors for EMS

5th step: In the Class List *EnergyManagementSystem:ConstructionIndexVariable*, both constructions defined in step 3 are declared as EMS variables which identify construction states for the program.

6th step: In *EnergyManagementSystem:Actuator*, the surfaces which have the dynamic insulation element incorporated, are inputted for EMS and this way identified as actuators

7th step: The control algorithm is introduced in *EnergyManagementSystem:Program*, which define how the actuator behaves throughout the simulation:

- IF $T_{in} > T_{out}$
- SET *ConstructionActuator* = Construction λ_2
- ELSE SET *ConstructionActuator* = Construction λ_1.

8th step: Finally, the program created in the previous step is declared and used as an input for EMS controls (on Class List *EnergyManagementSystem:ProgramCallingManager)*.

Field	Units	Obj1	Obj2	Obj3	Obj4
Name		Ins_ConstructSouth	Ins_ConstructWest	Ins_ConstructNorth	Ins_ConstructEast
Actuated Component Unique Name		SouthWall	WestWall	NorthWall	EastWall
Actuated Component Type		Surface	Surface	Surface	Surface
Actuated Component Control Type		Construction State	Construction State	Construction State	Construction State

Figure 3.6 – Example of an application of the Class List *EnergyManagementSystem:Actuator* which sets each surface as Surface: Construction State Actuators

3.2.3 – Preliminary results

In order to get familiar with the simulation tools and to understand if both approaches work the way it was expected, there is a need to get preliminary simulation results with a simple reference case. This way, the BESTEST Case 600 test building was selected to perform these analyses. This basic test building is a lightweight simple single-zone building which is assessed with a weather file from Denver, Colorado (USA) and has as temperature setpoints 20ºC for heating and 27ºC for cooling [41].

3.2.3.1 – MovableInsulation Actuator

In order to show the transition, in terms of temperature and energy demand, that occurs when MovableInsulation is used to change between insulated and non-insulated states, a simple scenario was designed. Based on schedules previously defined, the goal is to show that it is possible to change from one state to another throughout the simulation.

Two different periods were studied: one in the winter (21st-22nd of December) where the heating rate was assessed and another in the summer (21st- 22nd of June). For these two periods, three different scenarios were chosen:

- Always OFF, where the insulation layer was removed from the wall construction during the chosen period;
- Always ON, where the insulation layer is placed in the construction the same way as described in BESTEST Construction;
- 2nd Day OFF, where the insulation was only removed on the second day of the respective period.

The procedure followed for the summer period is illustrated in Figure 3.7.

[0001] Schedule:Compact

Field	Units	Obj1
Name		2nd Day OFF
Schedule Type Limits Name		Fraction
Field 1	varies	Through: 7/21
Field 2	varies	For: AllDays
Field 3	varies	Until: 24:00
Field 4	varies	1
Field 5	varies	Through: 7/22
Field 6	varies	For: AllDays
Field 7	varies	Until: 24:00
Field 8	varies	0
Field 9	varies	Through:12/31
Field 10	varies	For: AllDays
Field 11	varies	Until: 24:00
Field 12	varies	1

[0004] SurfaceControl:MovableInsulation

Field	Units	Obj1	Obj2	Obj3	Obj4
Insulation Type		Outside	Outside	Outside	Outside
Surface Name		SouthWall	NorthWall	WestWall	EastWall
Material Name		SinglePaneOpaque	SinglePaneOpaque	SinglePaneOpaque	SinglePaneOpaque
Schedule Name		2nd Day OFF	2nd Day OFF	2nd Day OFF	2nd Day OFF

Figure 3.7 – Methodology followed for the 2nd Day OFF Scenario at the summer period. Firstly the schedule described was defined and then it was used on the *SurfaceControl:MovableInsulation* Class List

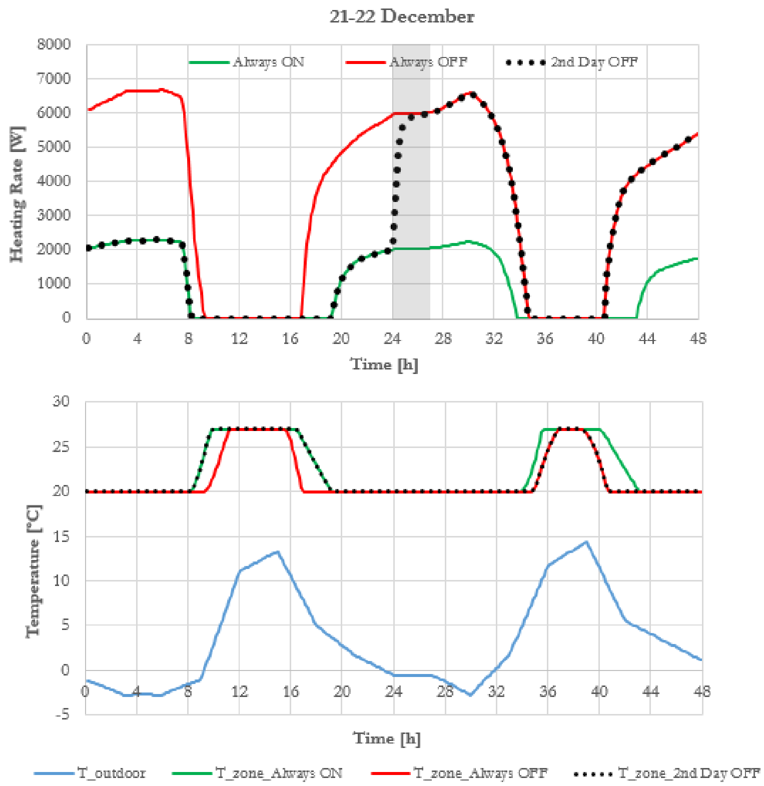


Figure 3.8 – Results from all the scenarios compared on the same plot for the winter period

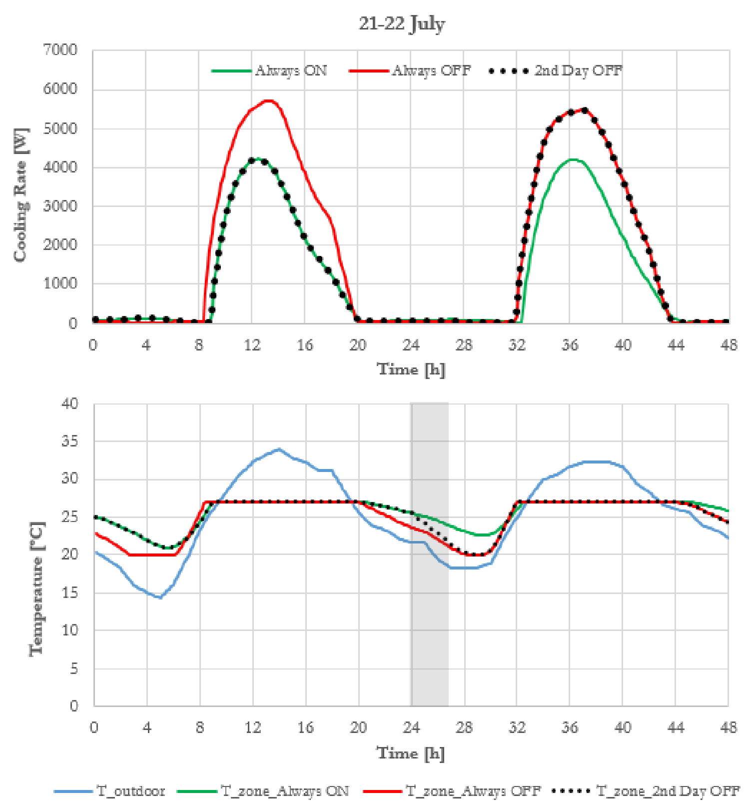


Figure 3.9 – Results from all the scenarios compared on the same plot for the summer period

On the winter period, illustrated in Figure 3.8, it is possible to observe the transition between one state and another in both periods (highlighted by the grey area in the graph). On the summer period, illustrated in Figure 3.9, the transition between Always ON and Always OFF states can be observed on the temperature graph whereas on the winter period the transition is observed on the heating rate profiles.

3.2.3.2 – Surface Construction State Actuator

In order to illustrate the way how this surface construction state actuator works inside the EMS and the effect it has on the output variables, a specific scenario with a specific control strategy was defined. Once more, it was used the BESTEST Case 600 as an input for the parameters of the model.

As control strategy, it was defined that when the temperature outdoors was higher than 25ºC, the actuator would change the standard BESTEST construction with a layer of insulation of 0.04 W/m.K of thermal conductivity (which I named *Walls_LowCond*) for another construction with a layer of insulation of 0.08 W/m.K (*Walls_HighCond*), at all the surfaces of the building. This algorithm introduced in the *Program* class list of EMS is presented in Figure 3.10.

The period chosen was between the 24th and 26th of August, and total cooling capacity was limited by 40% in order to allow a more significant variation on the indoor temperature.

[0001] EnergyManagementSystem:Program

Field	Units	Obj1
Name		ChangingConductivityProgram
Program Line 1		IF T_out > 25
Program Line 2		Set Ins_ConstructSouth = Walls_HighCond
A4		Set Ins_ConstructNorth = Walls_HighCond
A5		Set Ins_ConstructEast = Walls_HighCond
A6		Set Ins_ConstructWest = Walls_HighCond
A7		ELSE
A8		Set Ins_ConstructSouth = Walls_LowCond
A9		Set Ins_ConstructNorth = Walls_LowCond
A10		Set Ins_ConstructEast = Walls_LowCond
A11		Set Ins_ConstructWest = Walls_LowCond
A12		ENDIF

Figure 3.10 – EMS Program to change between low and high conductivity states

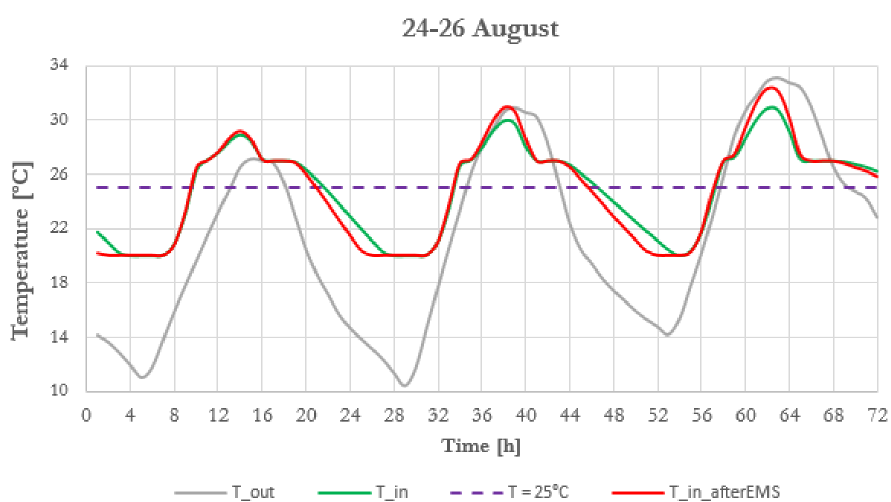


Figure 3.11 – Graph which illustrates the variability of the indoor temperature according to the EMS control strategy defined

As shown in Figure 3.11, a slight increase on the indoor temperature is registered on the last two days of the period, when the high conductivity construction overrides the low conductivity one. This way, it is possible to conclude that by having a higher conductivity construction in this period, the overheating problem is accentuated.

3.2.4 – Critical comparison

Besides the fact that it was proved, in the previous subchapter, that both approaches can be used to predict the performance of dynamic insulation elements, they have some limitations. Additionally, there is very limited guidance on how to use them.

When it comes to the use of the MovableInsulation actuator, it offers the advantage of acting at a material level, in contrast with the Surface Construction State Actuator that has to replace the whole construction of the given surface. Although, it is not clear what happens and how is it taken into account the solar heat previously stored in the material layer when this one is removed from the construction. The simplification assumed on this actuator led to different results between having the insulation ON in the MovableInsulation class list or just having it included in the Construction class list as usual. To finish with, by actuating with schedules, the MovableInsulation actuator cannot take into account the variability of thermophysical parameters of the envelope and its surrounding environment during the simulation, which is a major limitation.

Regarding the EMS Surface Construction State Actuator, it is much more extensive in terms of control strategies that can be used which makes it more promising than the other approach mentioned. However, it requires the different constructions to be assigned to have similar thermal/heat storage capacities. If it does not happen, the override action cannot be succeeded and the results can end up being physically inaccurate [40]. Throughout the simulations, I ran several times into a spatial discretization or nodal placement scheme problem, every time I increased the range of conductivities. This problem would not allow me to put the EMS control rules in practice because it blocked the possibility of overriding the constructions, as shown in Figure 3.12. A solution for this problem was not found, so I decided to carry on with my case study analysis using the MovableInsulation Actuator.

```
** Severe  ** InitEMSControlledConstructions: EMS Construction State Actuator not valid.
**   ~~~   ** Construction named = WALLS_LOWCOND has number of finite difference nodes =5
**   ~~~   ** While construction named = WALLS_HIGHCONDhas number of finite difference nodes =3
**   ~~~   ** This actuator is not allowed for surface name = SOUTHWALL, and the simulation continues without the override
** Severe  ** InitEMSControlledConstructions: EMS Construction State Actuator not valid.
**   ~~~   ** Construction named = WALLS_LOWCOND has number of finite difference nodes =5
**   ~~~   ** While construction named = WALLS_HIGHCONDhas number of finite difference nodes =3
**   ~~~   ** This actuator is not allowed for surface name = WESTWALL, and the simulation continues without the override
** Severe  ** InitEMSControlledConstructions: EMS Construction State Actuator not valid.
**   ~~~   ** Construction named = WALLS_LOWCOND has number of finite difference nodes =5
**   ~~~   ** While construction named = WALLS_HIGHCONDhas number of finite difference nodes =3
**   ~~~   ** This actuator is not allowed for surface name = NORTHWALL, and the simulation continues without the override
** Severe  ** InitEMSControlledConstructions: EMS Construction State Actuator not valid.
**   ~~~   ** Construction named = WALLS_LOWCOND has number of finite difference nodes =5
**   ~~~   ** While construction named = WALLS_HIGHCONDhas number of finite difference nodes =3
**   ~~~   ** This actuator is not allowed for surface name = EASTWALL, and the simulation continues without the override
```

Figure 3.12 – Error messages displayed after running EnergyPlus with EMS

Chapter 4 – Case study analysis

4.1 - Introduction

After doing a side-by-side comparison of the approaches available in EnergyPlus to predict the performance of dynamic insulation elements, an illustrative case study is needed to give physical interpretation of what do they mean and how can they be implemented in a real building. BESTEST is a reference case that allows to validate BPS software tools and to get familiar with these tools, but it represents a really simple case building, which is not so realistic and adequate to all the climates. Moreover, a case study should aim to solve a specific problem. On the analysis performed on the previous chapter, an actual problem is not presented because the goal was just to show how each approach works according to a specific control strategy. Thus, the focus on this case study will be on solving an overheating problem that occurs in the cooling season, when the capacity of the HVAC systems is limited. As mentioned in the previous chapter, the *MovableInsulation* actuator will be used in this analysis.

This chapter will start with a building model description, where the building geometry, construction, internal loads and HVAC system details will be given. Afterwards, the overheating problem will be analyzed and a control strategy for the dynamic insulation will be proposed.

4.2 – Building model description

In order to get meaningful results, a specific case study building was designed. The chosen climate was Lisbon, Portugal and the location of the building matches the one from the respective weather file (Latitude: 38.73N, Longitude: 9.15W) [42]. The goal here was to represent the mild southern European climate.

4.2.1 – Building geometry and construction details

A single-zone residential building with standard Portuguese construction which features increased insulation and improved glazing was chosen. This dwelling has a floor area of 72 m^2 (6 m depth and 12 m width) and has a height of 3 meters. It is turned south and has 4 windows of 5 m^2 on that surface. A shading device, with a width of 1.61 m, was designed in order to guarantee that the windows are fully shaded during the summer (Appendix I). This way, it was placed on the south façade above the windows. The geometry of the building was designed in SketchUp and then it passed to EnergyPlus through the OpenStudio plugin. An illustration of the building geometry is given in Figure 4.1.

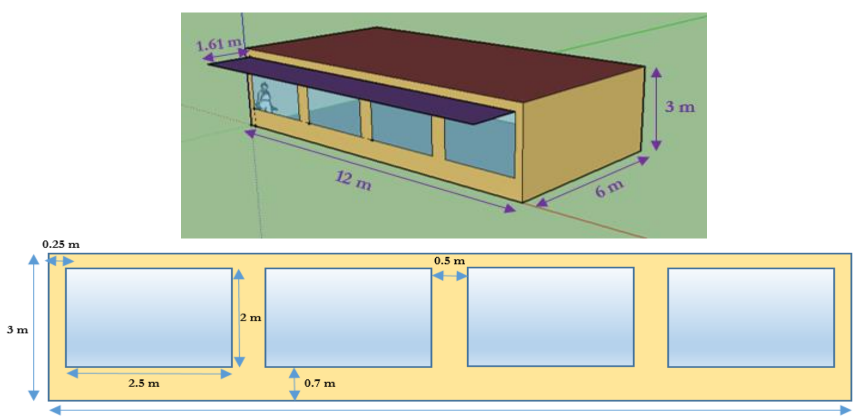


Figure 4.1 – Case study building geometry

In terms of construction materials layers, they are based on a standard Portuguese construction [43]. The order of the materials on the walls was changed in order to make it possible to model using the *MovableInsulation* approach, as it can only schedule insulation layers on the outside or inside layers of a certain surface but not in the middle. This way, instead of having a sequence, from outside to inside, of plaster (1 cm), hollow brick (11 cm), expanded polystyrene insulation (10 cm), hollow brick (15 cm) and plaster (1 cm), the insulation was chosen as outside layer (10 cm), and then a layer of 26 cm of brick followed by a 1 cm layer of plaster. This 10 cm layer of EPS, is the one that it is going to work as movable insulation, with an appropriate control strategy which will be defined and optimized later on. All the physical details about this exterior wall construction and also about floor and roof construction are given in Table 4.1.

Table 4.1 – Opaque elements for all the constructions (from outside to inside)

	Material	Thickness [m]	Thermal Conductivity [W/m.K]	Density [kg/m^3]	Specific heat [J/kg.K]
Walls	Expanded polystyrene insulation (EPS)	0.10	0.04	25	1500
	Hollow brick	0.26	0.72	1920	835
	Plaster	0.01	0.04	950	840
Floor	Expanded polystyrene insulation (EPS)	0.08	0.04	25	1500
	Heavyweight concrete	0.15	1.63	2300	800
Roof	Expanded polystyrene insulation (EPS)	0.15	0.04	25	1500
	Lightweight concrete	0.20	0.38	1200	840
	Plaster	0.01	0.04	950	840

In terms of translucent elements, double-glazed windows with Low-Emissivity were chosen. There are 4 windows, each of them with a U-value of 1.8 W/m^2.K and a solar factor of g = 0.63. All the windows are shaded by a shading static device of 1.61 m (Appendices II) in order to reduce the solar heat gains during the summer.

4.2.2 – Internal loads: lighting, people and equipment

In terms of internal loads, lighting, occupation and equipment profiles were added to EnergyPlus in order to have a realistic case study.

In terms of lighting, for a residential building (single-family) the power density is 5 W/m^2 [44] which is equivalent to 360 W in the single-zone case study building with 72 m^2 of floor area. Some additional input parameters for EnergyPlus are 0.4 for the return air fraction, 0.4 for the radiant fraction, 0.2 for the fraction visible and 1 for the fraction replaceable (default from EnergyPlus). In terms of the lighting schedule, an estimation of a standard usage was made, as shown in Table 4.2.

Table 4.2 – Lighting usage profile

Months	Days	Time of the day	Fraction
Through: December, 31	For: Weekdays Weekends AllOtherDays	Until: 07:00	0
		Until: 10:00	1
		Until: 18:00	0
		Until: 24:00	1

In terms of occupation, it was considered that there was one person per 17.70 m^2 of zone floor area (default from EnergyPlus), which for a floor area of 72 m^2 is equivalent to approximately 4 people. Each person has a metabolic rate of 115 W (70 W sensible and 45 W latent from which 30% is radiant), that corresponds to an adjusted rate (male/female) for a seated person with very light work [43]. This 115W is set as the activity level for all the year. In terms of the schedule for the occupation profile, it varies from cooling season (1st of July – 30th of September) to heating season (rest of the year), as shown in Table 4.3.

Table 4.3 – Occupation profile [43]

Months	Days	Time of the day	Fraction
Through: June, 30	For: Weekdays	Until: 10:00	1
		Until: 18:00	0
		Until: 24:00	1
	For: Weekends AllOtherDays	Until: 24:00	1
Through: September, 30	For: Weekdays	Until: 10:00	1
		Until: 18:00	0
		Until: 24:00	1
	For: Weekends AllOtherDays	Until: 11:00	1
		Until: 17:00	0
		Until: 24:00	1
Through: December, 31	For: Weekdays	Until: 10:00	1
		Until: 18:00	0
		Until: 24:00	1
	For: Weekends AllOtherDays	Until: 24:00	1

In terms of electric equipment, for a residential building (single-family) the power density is 5 W/m^2 [44] which is equivalent to 360 W in the single-zone case study building with 72 m^2 of floor area. This load is 100% sensible and has a radiant fraction of 0.5 (default from the EnergyPlus). The fractional schedule for the equipment usage was the same of the occupation profile.

4.2.3 – HVAC System

Regarding HVAC systems, constant setpoints of 20°C for heating and 25°C for cooling were considered. The design load for heating and cooling was determined by simulating the building in the design days for Lisbon, being the system dimensioned according to the lowest requirements (Appendix II). In terms of infiltration, it was set to 0.5 ACH, being constant throughout the year.

Overheating hours were defined as every hour where the indoor temperature was above 25°C. In order for that to happen, the HVAC cannot be an ideal load system, because it would always meet the temperature requirements. This way, the cooling capacity was limited. The value for this limit will be defined on the next chapter.

4.3 – Overheating problem analysis and respective control strategy

4.3.1 – Problem description

In the summer, problems regarding overheating are common in some dwellings, especially in a southern European country. In this case study, the application of dynamic insulation by means of using the *MovableInsulation* actuator have the goal of reducing the overheating problems resultant from not having an ideal load system but one with limited cooling capacity. As the focus of these analysis is to increase the thermal comfort by lowering the overheating, the percentage of overheating hours is the main performance indicator.

For the climate of Lisbon, the period during which overheating is a recurrent problem is during the cooling season. This period is between the 1st of July and the 30th of September, as defined on Lisbon's weather file [42]. This way, all the results that will be presented on the next chapter will be referring to that period.

4.3.2 – Control strategy

To deal with this problem, a control strategy was designed aiming to remove the unwanted heat gains accumulated during daytime, resultant of both solar and internal gains. The goal was to use the *MovableInsulation* actuator to remove or add the existent layer of insulation (10 cm of EPS) to the exterior walls construction considering three control parameters regarding the surrounding thermal environment: outdoor temperature (*Site Outdoor Air Drybulb Temperature*), indoor temperature (*Zone Mean Air Temperature*) and the solar radiation incident on the outside surface (*Surface Outside Face Incident Solar Radiation Rate per Area*).

As the goal of this case study analysis is to reduce the overheating problems, the control strategy was initially designed to remove the insulation layer when the indoor temperature was above 25°C. However, it is important to assure that, by removing the insulation layer, the problem will not get worse. So, it is of the utmost importance to assure that the outdoor temperature is not above the indoor temperature, and that the solar radiation incident on the surfaces is not higher than a reasonable value.

Chapter 5 – Results

5.1 – Introduction

After previously describing the case study that is going to be used, this chapter will present the results of a comparison between a base case with a limited cooling capacity, a case with movable insulation with an appropriate optimized control strategy and finally a case with natural ventilation. The goal here was to compare the effect between these two latter cases on the reduction of the overheating problem occurred on the base case. This analysis will be done for the cooling season, which is the period between the 1st of July and the 30th of September.

In order to perform the initial simulations, there was a need to define a suitable base control strategy for the movable insulation:

- The insulation layer will be removed in a specific surface whenever all the following conditions are met:
  - $T_{indoors}$ > 25°C (Overheating hours)
  - $T_{outdoors} < T_{indoors}$
  - Solar radiation incident on the surface ≤ 150 W/m^2
- There is the possibility to remove the insulation only on one of the surfaces, or all of them, depending on the value of the incident radiation on the East, West, North and South walls.
- If one of the conditions is not met on that surface, the insulation is set as active (‘ON’).

In the manner that the MovableInsulation approach only works through the use of control schedules, there is a need to run the simulation once to output these three parameters and perform a post-processing analysis in order to understand if all the conditions are verified for each surface. After evaluating the condition for each of the surfaces, a fractional schedule for each surface is imported from a comma separated values file (.csv) to the class list Schedule:File, which will feed the MovableInsulation actuator with the control schedule. This procedure is illustrated in Figure 5.1.

[0004] Schedule:File

Field	Units	Obj1	Obj2	Obj3	Obj4
Name		EastMovableInsControl	NorthMovableInsControl	WestMovableInsControl	SouthMovableInsControl
Schedule Type Limits Name		Fraction	Fraction	Fraction	Fraction
File Name		control_movableins.csv	control_movableins.csv	control_movableins.csv	control_movableins.csv
Column Number		1	2	3	4
Rows to Skip at Top		1	1	1	1
Number of Hours of Data		8760	8760	8760	8760
Column Separator		Comma	Comma	Comma	Comma
Interpolate to Timestep		No	No	No	No
Minutes per Item					

[0004] SurfaceControl:MovableInsulation

Field	Units	Obj1	Obj2	Obj3	Obj4
Insulation Type		Outside	Outside	Outside	Outside
Surface Name		EastWall	NorthWall	WestWall	SouthWall
Material Name		EPS 10 cm	EPS 10 cm	EPS 10 cm	EPS 10 cm
Schedule Name		EastMovableInsControl	NorthMovableInsControl	WestMovableInsControl	SouthMovableInsControl

Figure 5.1 – Control strategy applied in EnergyPlus. First the *Schedule:File* class list imports the control schedule for each surface from the .csv file which will be used as input for the *MovableInsulation* class list

5.2 – Base case

Before defining the base case, the first step was to determine which was the cooling capacity to be considered to size the HVAC system. In order to do that, the model was first simulated with an unlimited cooling capacity to determine the maximum capacity of the HVAC system.

The next step was to limit the cooling capacity for 80%, 60%, 40% and 20%, in the class list *HVACTemplate:Zone:IdealLoadsAirSystem*, on the field *Maximum Total Cooling Capacity*, and demonstrate the effect of the movable insulation using each limit of cooling capacity. The goal of this analysis was to select the suitable cooling capacity for the following analysis.

Furthermore, the model was simulated with each cooling capacity limits and the movable insulation was introduced with the base control strategy mentioned before.

Table 5.1 - Results for different cooling capacities, before and after the application of the movable insulation

Cooling Capacity	Cooling [MWh]			% Overheating hours			ΔT_{Max}	$T_{in,Max}$ [°C]	
	Before	After Mov. Ins.		Before	After Mov.Ins.			Before	After Mov. Ins.
80%	2.217	1.514	(-31.7%)	12.9%	1.7%	(-11.2%)	0.9	26.2	25.6
60%	2.156	1.548	(-28.2%)	46.7%	17.9%	(-28.8%)	1.3	27.4	26.6
40%	1.703	1.459	(-14.4%)	91.5%	65.7%	(-25.8%)	2.1	29.4	28.4
20%	0.819	0.812	(-0.9%)	100.0%	98.6%	(-1.4%)	2.4	31.9	31.1

After analyzing the results of the previous simulations, referred in Table 5.1, a cooling capacity of 40% was chosen for the base case, as it allows a significant reduction on the overheating hours as well as a high difference between the indoor temperatures before and after the application of the movable insulation system (ΔT_{Max}).

Table 5.2 – Base case results

Cooling [MWh]	% Overheating hours	$T_{in,Max}$ [°C]
1.703	91.5%	29.4

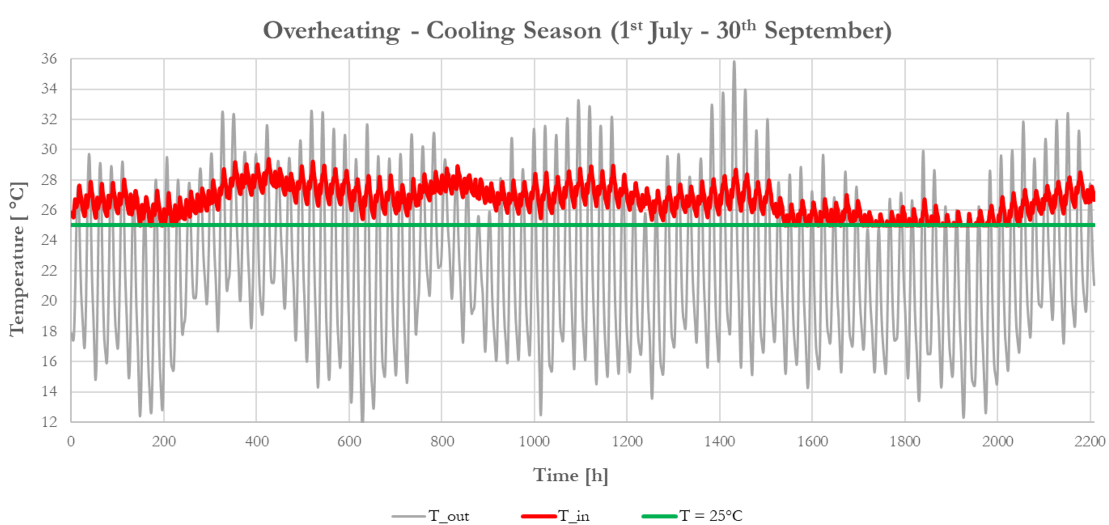


Figure 5.2 – Cooling season on the base case where the overheating problem is highlighted

Considering the assumptions previously referred and taking into account the results obtained, illustrated by Table 5.2 and Figure 5.2, the base case, which is characterized by having overheating during almost 92% of the cooling season, is presented as the basis of comparison for the following cases.

5.3 – Optimization of the control strategy: Movable Insulation case

After defining the overheating problem, by means of the base case, the objective was to develop a movable insulation case with an optimized control strategy. By optimizing the parameters of the control strategy, the goal is to lower the overheating hours and the cooling demand to a minimum.

The first parameter to be optimized was the limit of incident solar radiation below which the insulation layer is set as not active/'OFF' and above which the insulation layer is set as active/'ON' (with the appropriate indoor and outdoor temperatures). Thus, the simulation was repeated between 0 W/m^2 (night period) and 850 W/m^2 (the maximum incident radiation registered during the cooling season).

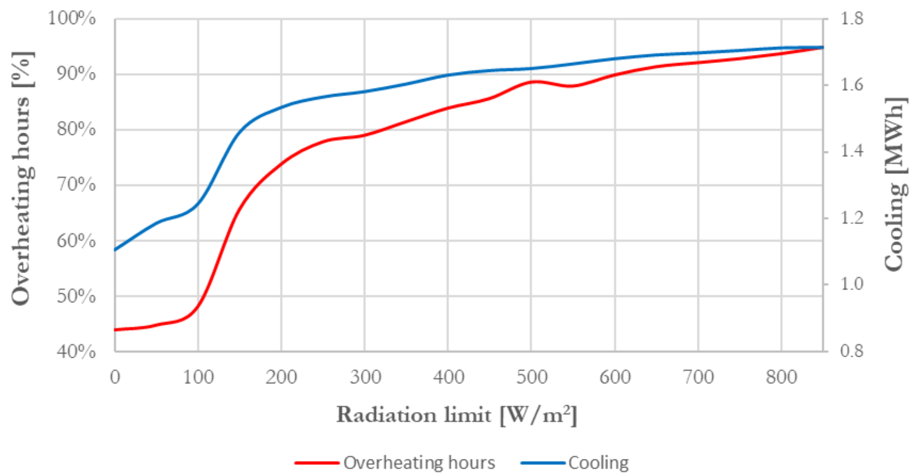


Figure 5.3 – Radiation limit optimization

As represented in the graph of Figure 5.3, the overheating hours and the cooling demand are minimum when the limit of the incident solar radiation is 0 W/ m^2, which is mainly during nighttime.

The second parameter to be optimized was the limit of the indoor temperature, above which the insulation layer is ON and below which the insulation is OFF (with the appropriate outdoor temperature). The intention of this analysis was to determine if by activating the movable insulation 'earlier' it would be possible to decrease the overheating problem. As the minimum indoor temperature registered on the base case was 24°C, the simulation was repeated for this temperature.

Table 5.3 – Indoor temperature optimization

T_{in} [°C]	Cooling [MWh]	% Overheating hours
25	1.107	44.0%
24	1.107	40.4%

As presented in Table 5.3, by setting a limit to the indoor temperature to 24°C used for the control strategy of the movable insulation, it is possible to decrease the overheating hours in 3.6% in comparison with the case of using 25°C as a limit.

After optimizing the parameters of the control strategy, the insulation layer will be removed in a specific surface whenever all the following conditions are met:

- $T_{indoors} > 24°C$
- $T_{outdoors} < T_{indoors}$
- Solar radiation incident on the surface = 0 W/m^2 (night period)

Table 5.4 – Comparison between the results of the thermal simulation on the base case and on the movable insulation case

	Cooling [MWh]	% Overheating hours	ΔT_{Max}	$T_{in,Max}$ [°C]
Base Case	1.703	91.5%	-------	29.4
Movable Insulation Case	1.107 (-35.0%)	40.4% (-51.1%)	2.6	27.5

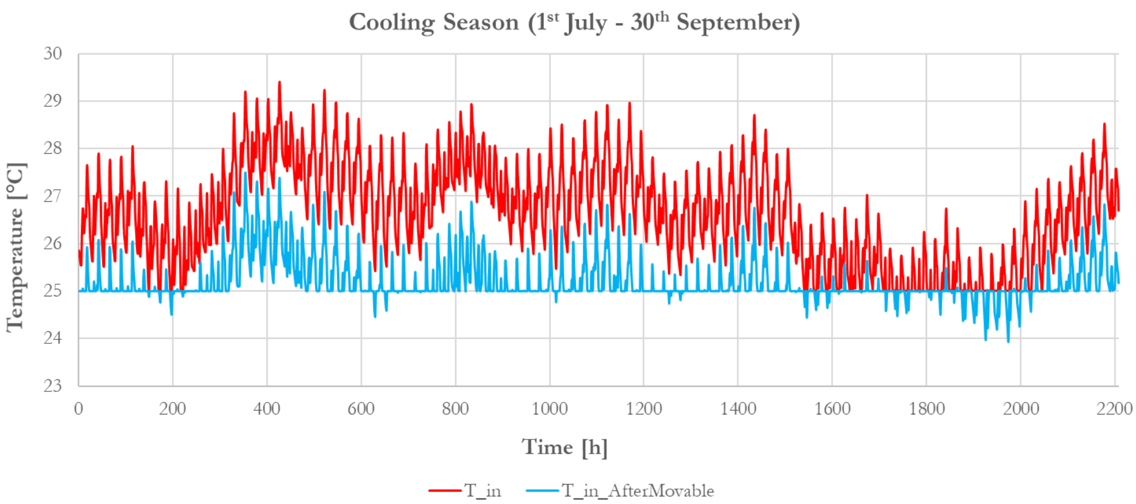


Figure 5.4 – Illustration of the application of the control strategy on the indoor temperature during the cooling season

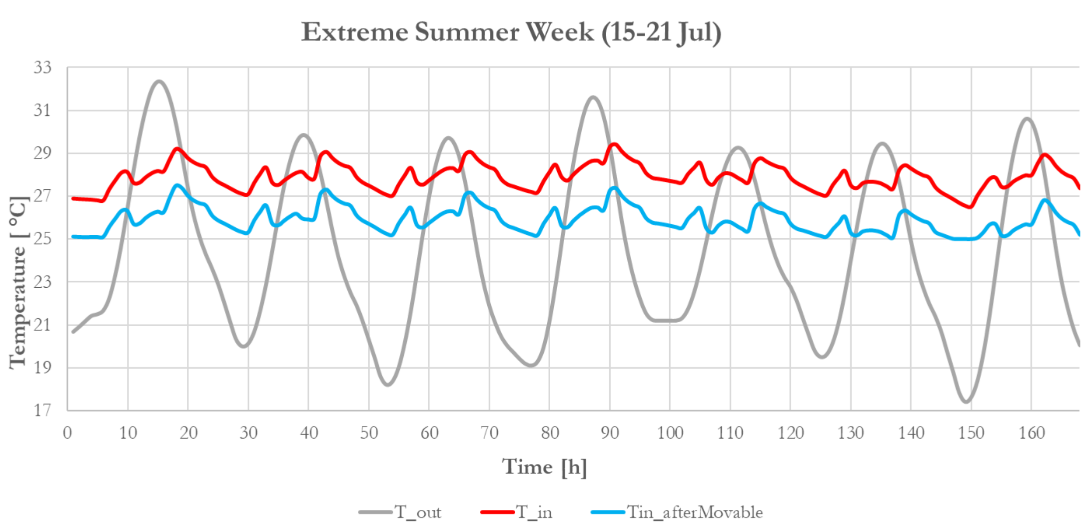


Figure 5.5 – Illustration of the effect of the movable insulation during the extreme summer week in Lisbon

By analyzing the graph illustrated in the Figure 5.4, it is possible to identify the effect of the movable insulation in the reduction of the overheating problem during the cooling season. With this optimized control strategy, it was possible to reduce in about 51% of the overheating hours and 35% of the cooling demand in comparison with the base case, as referred in Table 5.4. In order to have better view of what is happening, a close-up on the extreme summer week was done as exhibited in Figure 5.5.

In order to illustrate a graphical understanding of how the control strategy works, it is shown in Figure 5.6 a side-by-side comparison of all the parameters taken into account to control the movable insulation layer on the north façade, for a period of 3 days (15-17 of July). The black dashed line illustrates the state of the movable insulation: when it is 0 (lower position), the insulation layer is 'OFF' and when it is 1 (upper position), it is 'ON'. It is important to refer that the variable *T_in_AfterMovable* also takes into account the other surfaces (East, West and South façades). By analyzing this graph, it is possible to conclude that the control strategy is working the way it should.

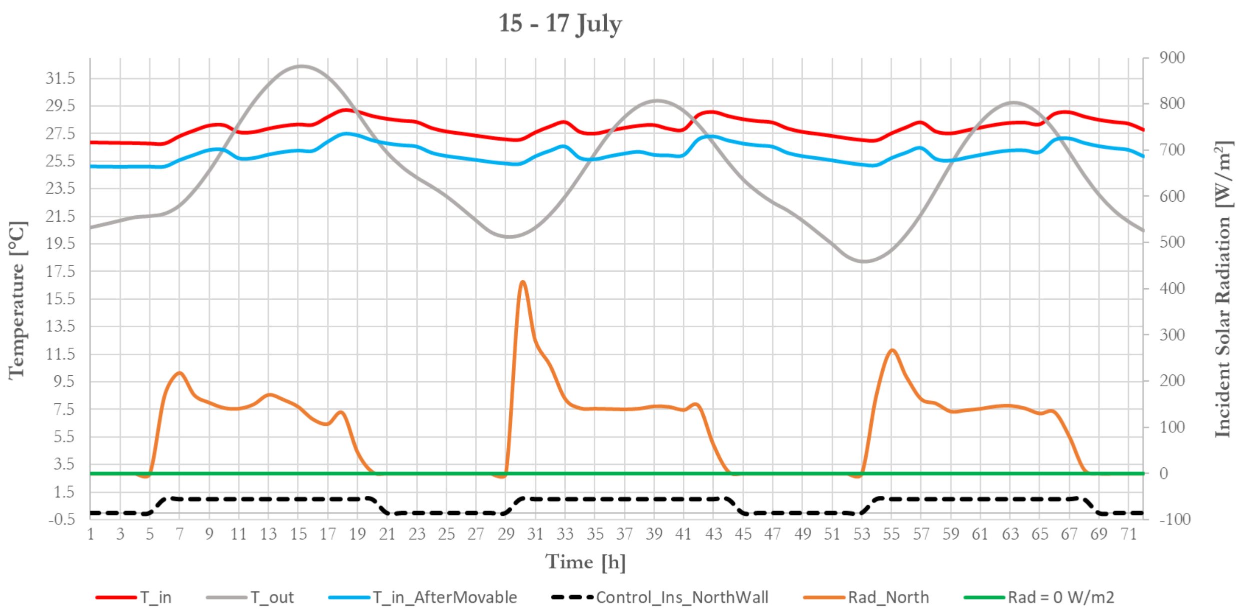


Figure 5.6 – Illustration of the way of functioning of the control strategy, on the North Wall, during 3 summer days in July

5.4 – Natural ventilation case vs Movable insulation case

In this scenario, the goal was to compare the effect of the movable insulation with an optimized control strategy with a system of natural ventilation with a ventilation rate of 5 ACH. In practice, the idea was to compare the previously applied movable insulation system with the action of opening a window, when overheating is occurring. After doing this comparison, an additional scenario with the combination of movable insulation and natural ventilation will be presented.

To apply this case, as in the movable insulation case, the objective was to come up with a proper control strategy in order to reach the desirable goal of reducing the overheating problem. As the main source of heat transfer, in this case, is convection, radiation was not a parameter considered. However, it was necessary to have a lower limit of the outdoor temperature above which the natural ventilation is allowed, to avoid the entrance of air with really low temperatures, which would require an additional heating demand.

This way, the following control strategy was proposed:

- The natural ventilation is ON when all the following conditions are met:
  - $T_{indoors} \geq 24°C$
  - $T_{outdoors} < T_{indoors}$
  - $15°C < T_{outdoors} < 24°C$

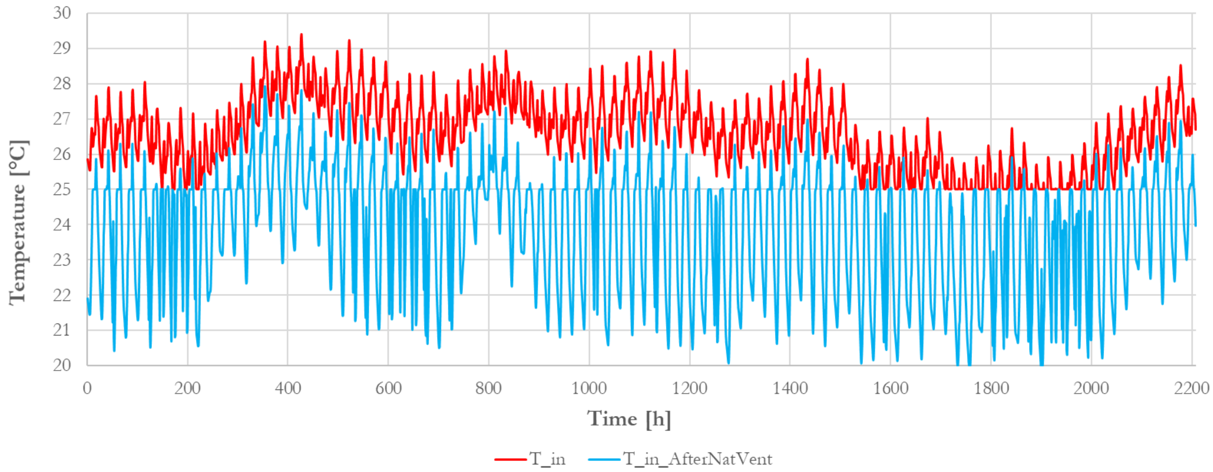


Figure 5.7 – Illustration of the effect of the natural ventilation on the indoor temperature during the cooling season

Table 5.5 – Comparison between the results of the thermal simulation on the base case and on the natural ventilation case

	Cooling [MWh]	% Overheating hours	ΔT_{Max}	$T_{in,Max}$ [°C]
Base Case	1.703	91.5%	-------	29.4
Movable Insulation Case	1.107 (-35.0%)	40.4% (-51.1%)	2.6	27.5
Natural Ventilation Case	0.558 (-67.2%)	23.5% (-68.0%)	5.8	27.9

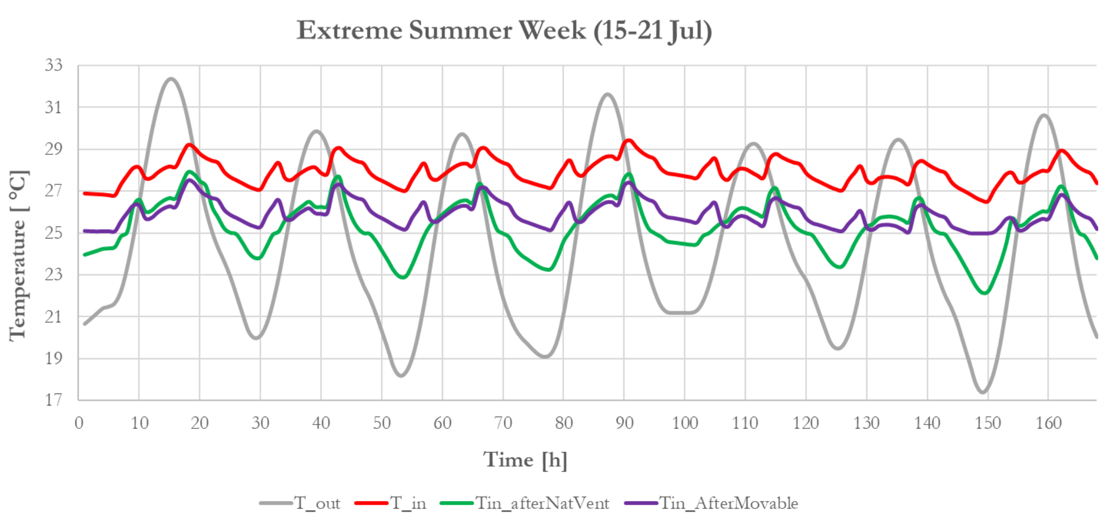


Figure 5.8 – Comparison between the effect of the movable insulation and the natural ventilation during the extreme summer week in Lisbon

After analyzing the results shown in Table 5.5 and illustrated by Figure 5.7, one can conclude that the magnitude of reduction on the overheating, registered on the base case, is significantly greater in the natural ventilation case in comparison with the movable insulation case. The cooling demand reduction and the maximum difference of temperature doubles the ones from the movable insulation case whereas the overheating hours are about 17% less. Looking at the Figure 5.8, it is possible to conclude that the major reduction on the indoor temperature occurs during the night period.

5.5 – Combination of movable insulation and natural ventilation

From the last sub-section, it was clear that the natural ventilation has a bigger impact on the reduction of the overheating problem, registered on the base case, in comparison with the movable insulation case. Moreover, it was interesting to find out if even though that happens, the use of the movable insulation in combination with the natural ventilation can still contribute to decrease both cooling demand and the percentage of the overheating hours.

Table 5.6 – Summary of the results

	Cooling [MWh]	**% Overheating hours**	**ΔT_{Max}**	**$T_{in,Max}$ [°C]**
Base Case	1.703	91.5%	-------	29.4
Movable Insulation Case	1.107 (-35.0%)	40.4% (-51.1%)	2.6	27.5
Natural Ventilation Case	0.558 (-67.2%)	23.5% (-68.0%)	5.8	27.9
Combination	0.310 (-72.0%)	11.2% (-80.3%)	6.4	26.9

As Table 5.6 shows, the combination of both cases proves to be an interesting solution to lower even more the cooling demand and the percentage of overheating hours. In comparison with the base case, the combination of movable insulation and natural ventilation allows a reduction of 72.0% on the cooling demand and 80.3%.

Chapter 6 – Conclusions and future work

Dynamic insulation elements offer plenty of opportunities in comparison with static conventional insulation elements. The idea of "switching off" the insulation allows the possibility of controlling the heat flux through the facades, which brings a significant potential for thermal comfort improvements and energy savings. As presented in Chapter 2, there are so many different possibilities of systems/materials that can be used to achieve different adaptive ranges with different control mechanisms. However, there is very little knowledge of how to turn these opportunities and these potential benefits into real strengths, because the information available is still vague. This lack of information can turn these strengths into weaknesses, because it cannot make the user to conclude that these systems are competitive and cost-effective, which will therefore limit the product development.

When it comes to predict the performance of dynamic insulation elements, there is very little guidance for the user of the BPS tools as there is not any established assessment framework, which constitutes a threat. The goal of this research was to assess how can we use modelling and simulation tools to overcome this threat by determining how dynamic insulation elements can be assessed. This way, the weaknesses regarding technology development would be reduced while increasing the strengths.

In chapter 3, two different approaches available in EnergyPlus to predict the performance of dynamic insulation elements were critically compared. Theoretically, the EMS approach using the Surface Construction State seems to show more potential but due to some interface limitations or the way it has been implemented, it has a lot of practical limitations. This led me to pick the MovableInsulation Actuator for the case study analysis.

Moreover, in the case study analysis, it was possible to conclude that by using an optimized control strategy, it is possible to achieve significant thermal comfort improvements, by reducing the percentage of overheating hours in about 51%, and by lowering the cooling demand by 35%. However, an approach of a natural ventilation case to solve the overheating problem was way more effective as it allowed for a reduction of an additional 32% on the cooling demand and 17% on the percentage of overheating hours. It was also shown that by using the two approaches together, it is possible to achieve even greater reductions.

Besides the fact that I succeeded partly to eliminate the threats by doing an expositive critical analysis of the different approaches available and its application in EnergyPlus, there is still much work that needs to be done before it is possible for the concept of dynamic insulation to be a firm reality. To achieve that goal, the weaknesses and the threats, from the technology side and from the simulation side must be eliminated. It is important to better understand how can a user take advantage of the potential of the EMS Surface Construction State Actuator to predict the performance of dynamic insulation elements, as it is more promising than the MovableInsulation approach, which only works on the basis of schedules. But first, a solution for some of the implementation errors, which I faced throughout the project, must be found.

Finally, there is also a need to conclude about what is the most promising type of building for the application of these elements. Additionally, what is the potential of the thermal mass together with dynamic insulation elements and what is the effect of different construction details on the thermal load delay represent some questions that need to be answered in order to assess about what is the best or more appropriate control strategy for dynamic insulation elements. In order to push the application of the concept further, there is a need to do more case study analysis and more measurements in different climates.

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Appendices

1 – Shading device width sizing

The purpose to design a shading device to be used in the case study analysis was to reduce the unwanted solar heat gains through the windows during the cooling season. This can be achieved by sizing the width of the shading device for the Autumn Equinox (21st of September) at mid-day. This way, windows will be shaded during the period between Spring and Autumn Equinoxes (21st March – 21st September). [45]

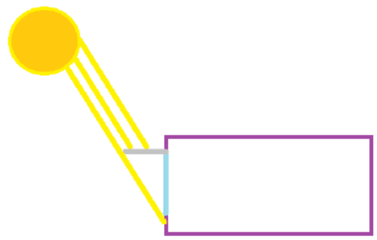

Figure A.1 – Desired effect of the shading device during the cooling season

To calculate the width of the shading device, it is necessary to calculate the solar altitude α (and consequently the solar declination, δ) for the latitude of Lisbon (ϕ = 38.7°), at the 21st of September (Julian Day 264) at mid-day (Hour Angle, HRA = 12) [46]. After calculating the solar altitude, the height of the window times the tangent of the complementary angle of the solar altitude gives us the width of the shading device.

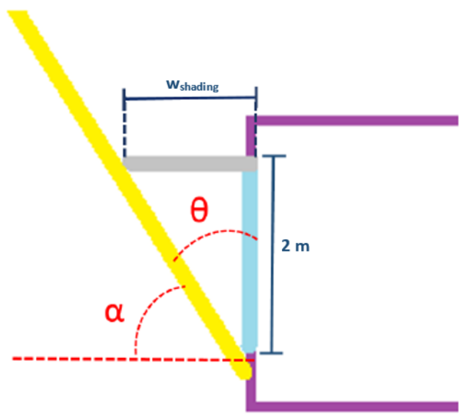

Figure A.2 – Angle geometry to calculate the width of the shading device

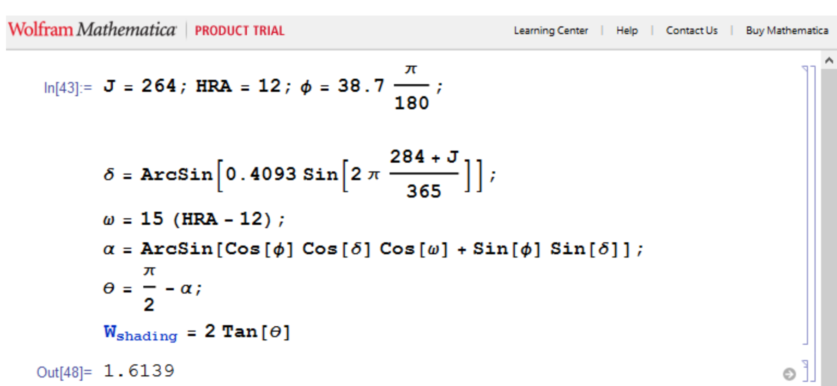

Figure A.3 – Calculation of the width of the shading device, on Wolfram Mathematica

II – Additional input simulation and system sizing parameters

In this appendix, there will be mentioned some of the parameters which were given as input for the simulation, which was performed on EnergyPlus, version 8.3.

Table A.1 – Simulation parameters

Surface Convection Algorithm for indoor surface	TARP
Surface Convection Algorithm for outside surface	DOE-2
Heat Balance Algorithm	Conduction Transfer Function (CTF)
Loads Convergence Tolerance Value	0.04
Temperature Convergence Tolerance Value	0.4
Solar Distribution	FullInteriorAndExterior
Maximum Number of Warmup Days	25
Minimum Number of Warmup Days	6
Number of Timesteps per Hour	6 (1 per each 10 minutes period)

The site location was the same of the weather data for Lisbon, Portugal (Latitude: 38.73 N, Longitude: 9.15 W, Time zone: GMT (0), Elevation: 71 m). The information about the design days and the ground temperature was also retrieved from the weather data. *[42]*

Table A.2 – Sizing Period: Design Days for Lisbon [42]

	Winter Design Day	**Summer Design Day**
Date	January, 21	August, 21
Maximum Dry-Bulb Temperature	4.2°C	34.2°C
Daily Dry-Bulb Temperature Range (Δ°C)	0	10.1
Wet bulb or Dew Point at Maximum Dry-Bulb	4.2°C	20°C
Barometric Pressure	100475 Pa	100475 Pa
Wind Speed	2.2 m/s	4.4 m/s
Wind Direction	50°	330°
Sky Clearness	0	1

Table A.3 – Monthly undisturbed ground temperature values, for 2.0 m depth, in GroundTemperature:BuildingSurface [42]

January	13.2
February	12.3
March	12.5
April	13.2
May	15.5
June	17.7
July	19.4
August	20.3
September	20.1
October	18.9
November	16.9
December	14.9